PB85-181097

Mutagenicity and Carcinogenicity Assessment of 1,3-Butadiene. Review Draft

(U.S.) Environmental Protection Agency
Washington, DC

Feb 85

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Office of Health and
Environmental Assessment
Washington DC 20460

EPA/600/8-85/004A
February 1985
Review Draft

Research and Development

PB85-181097

EPA

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA/600/8-85/004A	2.
3. RECIPIENT'S ACCESSION NO. PB85 181097/AS	
4. TITLE AND SUBTITLE MUTAGENICITY AND CARCINOGENICITY ASSESSMENT OF 1,3-BUTADIENE Review Draft	5. REPORT DATE February 1985
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) See list of authors, reviewers, and contributors	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Same as 12	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Office of Health and Environmental Assessment Office of Research and Development U.S. Environmental Protection Agency Washington, DC 20460	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA/600/21
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

The Mutagenicity and Carcinogenicity Assessment of 1,3-Butadiene was prepared to serve as a source document for Agency-wide use. In the development of this assessment document, the scientific literature has been inventoried, key studies have been evaluated, and the summary and conclusions have been prepared so that the mutagenicity, carcinogenicity, and related characteristics of 1,3-butadiene are qualitatively identified. Measures of dose-response relationships relevant to ambient exposures are also discussed so that the adverse health responses are placed in perspective with possible exposure levels.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES 106
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

DRAFT
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EPA/600/8-85/004A
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OF

1,3-BUTADIENE

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Office of Research and Development
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CONTENTS (1,3-Butadiene)

Preface. v
Authors, Contributors, and Reviewers vi

1. SUMMARY AND CONCLUSIONS 1

1.1. Summary 1
1.2. Conclusions 5

2. INTRODUCTION 7

3. MUTAGENICITY OF 1,3-BUTADIENE AND ITS REACTIVE METABOLITES 9

3.1. Mutagenicity of 1,3-Butadiene. 9
3.2. Metabolism of 1,3-Butadiene and Reaction of Metabolites with DNA 10
3.3. Mutagenicity of 3,4-Epoxybutene. 13
3.4. Genotoxicity of 1,2:3,4-Diepoxybutane. 14

3.4.1. Studies in Bacteria. 14
3.4.2. Studies in Fungi 15
3.4.3. Studies in Mammalian Cells 17
3.4.4. *In vivo* Studies. 19

3.5. Summary of Mutagenicity Studies. 26

4. CARCINOGENICITY. 27

4.1. Toxicology and Pharmacokinetics. 27
4.2. Animal Studies 29

4.2.1. Chronic Toxicity Studies in Mice 29
4.2.2. Chronic Toxicity Studies in Rats 35
4.2.3. Summary of Chronic Toxicity Studies. 39

4.3. Epidemiologic Studies. 39

4.3.1. McMichael et al. (1974, 1976). 41
4.3.2. Andjelkovich et al. (1976, 1977) 44
4.3.3. Checkoway and Williams (1982). 50
4.3.4. Meinhardt et al. (1982). 52
4.3.5 Matanoski et al. (1982). 55
4.3.6. Summary of Epidemiologic Studies 59

4.4. Quantitative Estimation. 62

4.4.1. Procedures for Determination of Unit Risk. 62

4.4.1.1. Description of the Low-Dose Extrapolation Model 64
4.4.1.2. Selection of Data. 67

CONTENTS (continued)

4.4.1.3. Calculation of Human Equivalent Dosages from Animal Data 68

4.4.1.4. Calculation of the Unit Risk from Animal Studies 70

4.4.1.4.1. Adjustments for Less Than Lifetime Duration of Experiment. 70

4.4.1.5. Interpretation of Quantitative Estimates. 71

4.4.1.6. Alternative Models 72

4.4.2. Calculation of Quantitative Estimates. 73

4.4.3. Comparison of Human and Animal Inhalation Studies 76

4.4.4. Relative Potency 84

4.4.5. Summary of Quantitative Estimation 90

REFERENCES. 92

PREFACE

The Mutagenicity and Carcinogenicity Assessment of 1,3-Butadiene was prepared to serve as a source document for Agency-wide use. This document was developed primarily for use by the Office of Air Quality Planning and Standards to support decision-making regarding possible regulation of 1,3-butadiene as a hazardous air pollutant.

In the development of the assessment document, the scientific literature has been inventoried, key studies have been evaluated, and the summary and conclusions have been prepared so that the mutagenicity, carcinogenicity, and related characteristics of 1,3-butadiene are qualitatively identified. Measures of dose-response relationships relevant to ambient exposures are also discussed so that the adverse health responses are placed in perspective with possible exposure levels.

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1. SUMMARY AND CONCLUSIONS

1.1. SUMMARY

1,3-butadiene is a colorless gas with a slight aromatic odor at room temperature and pressure. It is used mainly by the styrene-butadiene rubber and polybutadiene rubber industries. No deaths and very few toxic effects have been reported from acute exposure to the vapor. The symptoms resulting from acute exposures are lethargy, drowsiness, and irritation to the mucous membranes of the eyes and the mouth.

The available information on the mutagenicity of 1,3-butadiene is quite limited in that only two studies have been reported. Both studies, however, indicate that 1,3-butadiene is a mutagen in Salmonella typhimurium. The mutagenicity is observed only in the presence of a liver S9 metabolic activation system. No whole animal studies have been reported. These results suggest that 1,3-butadiene is a promutagen in bacteria (i.e., its mutagenicity depends on metabolic activation).

There is no information on the metabolism of 1,3-butadiene in humans. In vitro data suggest that 1,3-butadiene is metabolized to 3,4-epoxybutene and then to diepoxybutane. Preliminary evidence in rats suggests that 1,3-butadiene is metabolized to 3,4-epoxybutene in vivo (Bolt et al., 1983), indicating that the metabolic pathway outlined on the basis of in vitro data may occur in vivo. More detailed studies by Bolt and his coworkers have been published recently; the results of these studies will be included in the final document.

3,4-Epoxybutene is a monofunctional alkylating agent and is a direct-acting mutagen in bacteria. It has been tested in Klebsiella pneumoniae and

Escherichia coli. Diepoxybutane is a bifunctional alkylating agent, and as such it can form cross-links between two strands of DNA. It is mutagenic in bacteria (K. pneumoniae and S. typhimurium), fungi (yeast and Neurospora crassa), and the germ cells of Drosophila melanogaster. It also induces DNA damage in cultured hamster cells and in mice, is clastogenic in fungi and cultured rat cells, and produces chromosome damage/breakage in D. melanogaster germ cells. Therefore, there is strong evidence that diepoxybutane is a mutagen/clastogen in microbes and animals.

Two lifetime inhalation carcinogenicity studies have been carried out in mice and rats. There was a marked increase in incidences of primary tumors among the exposed groups of mice in both sexes. These tumors included lymphomas, hemangiosarcomas, alveolar/bronchiolar adenomas (and carcinomas), acinar cell carcinomas, granulosa cell tumors or carcinomas, forestomach papillomas and carcinomas, and hepatocellular adenomas and carcinomas. The study had to be terminated at 60-61 weeks instead of the planned 104 weeks because of excessive deaths from the neoplasia among the exposed mice.

In female rats (Sprague-Dawley) exposed to 1,3-butadiene, increased incidences of mammary tumors, thyroid follicular cell adenomas, and uterine stromal sarcomas were observed. In the male rats, increases in tumor incidences were found in the exposed animals in the form of Leydig cell tumors and exocrine pancreatic adenomas. Zymbal gland tumors were increased in both sexes of exposed rats. The tumor sites involved were different in the mice and rats among the exposed groups. The severity of the cancers was also widely different; in the rats, no increase in mortality secondary to neoplasia was observed, and there was no early termination of the experiments. In addition to the differences found in the two sexes, rats were affected less than mice.

Epidemiologic studies of the potential health hazards associated with 1,3-butadiene exposure are limited. There are a number of occupational studies of rubber workers, but only a few of these studies were considered relevant for this review. These studies concerned workers who were specifically identified as having worked in the production of synthetic 1,3-butadiene rubber or as having worked in a synthetic rubber plant. Of the three studies on workers specifically identified as being exposed to styrene-1,3-butadiene, two of them also included workplace air sampling. In one study, air samples were analyzed for 1,3-butadiene, styrene, and benzene. In the other study, the air concentrations for 1,3-butadiene, benzene, styrene, and toluene were reported. Both of these studies found that the time-weighted average for each of the chemical exposures examined was well below the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLV) at that time for these chemicals (1,3-butadiene: TLV = 1,000 ppm; styrene: TLV = 100 ppm; toluene: TLV = 100 ppm; benzene: TLV = 10 ppm). One of the studies was a cross-sectional investigation designed to look at certain hematologic parameters. This investigation revealed no evidence of any hematologic abnormality in the study population.

A case-control study of deaths among rubber plant workers from cancer of certain sites, diabetes mellitus, and ischemic heart disease found workers in the synthetic rubber area of the plant to have the highest risk ratio for deaths from lymphatic and hematopoietic cancer (ICD 200-209). The same authors, however, had previously found an association of lymphatic leukemia cancer deaths with organic solvent exposures in the rubber industry.

A cohort study of styrene-butadiene rubber (SBR) workers found that the Standardized Mortality Ratio (SMR) for lymphatic and hematopoietic cancer was of borderline significance for a subcohort of workers employed at one plant

during the time when a batch production process was in operation. Here again, solvent exposure may have been a confounding factor. There is also some limited evidence that styrene may be a carcinogen, and in particular, a leukemogen. This factor poses further complications for evaluating the epidemiologic studies of SBR workers with regard to 1,3-butadiene.

A cohort mortality study of rubber plant workers found that an excess of lung cancer deaths occurred among workers in the synthetic rubber area of the plant. This was based on only three deaths, however, and there was no control for smoking.

A large cohort study of almost 14,000 SBR workers at eight plants found none of the SMRs for cancer to be significantly elevated. Some bias may have occurred, however, due to a possible underascertainment of total deaths and a possible overestimation of deaths among blacks. Given the inconsistency of results from different studies, the possible confounding due to exposure to solvents, styrene, and possibly other chemicals, and the potential biases in some of the studies, the epidemiologic data would have to be considered inadequate for evaluating whether a causal association exists between 1,3-butadiene exposure and cancer in humans.

Based on the linearized multistage model, a maximum likelihood estimate of incremental unit risk was calculated for 1,3-butadiene, using the geometric mean from the pooled male and pooled female significant tumor responses of the NTP mouse study. The mean value of $q_1 = 9.0 \times 10^{-3}$ (ppm) was then used to predict human responses in several epidemiologic studies, and the predicted and actual responses were compared. The comparisons were hampered by a scarcity of information concerning actual exposures, age distributions, and work histories. In addition, because there was no consistent cancer response across all of the studies, the most predominant response, cancer of the lymphatic and hemato-

poietic tissues, was chosen as being the target for 1,3-butadiene. Based on the comparisons between the predicted and observed human response, the extrapolated unit risk value from the mice data appeared slightly high, but in view of the uncertainties in the epidemiologic data, no better estimate can be made at this time.

1.2. CONCLUSIONS

1,3-butadiene has been shown to be an indirect mutagen in bacteria. One of its potential metabolites, diepoxybutane, is mutagenic in prokaryote as well as eukaryote test systems. Exposure of rodents to 1,3-butadiene results in ovarian tumors in mice (Huff et al., 1985) and testicular tumors in rats (Hazleton Laboratories Europe, Ltd., 1981a). Therefore, these data are suggestive that 1,3-butadiene may present a heritable risk to humans. However, additional studies in mammalian test systems, as outlined in the Agency's Proposed Guidelines for Mutagenicity Risk Assessment (1984), should be conducted to further characterize the mutagenic potential of 1,3-butadiene.

On the basis of sufficient evidence from studies in two species of rodents, and inadequate epidemiologic data, 1,3-butadiene can be classified, according to the International Agency for Research on Cancer (IARC) classification scheme, as a "probable" human carcinogen, Group 2B. It was placed in Sub-Group B because of the inadequacy of the available epidemiologic data. Using the newly proposed EPA classification scheme for carcinogenicity evidence, the ranking would be B2, meaning that 1,3-butadiene is a "probable" human carcinogen.

Using a linearized multistage model, a 95% upper-limit incremental unit risk for 1,3-butadiene is estimated from a NTP mouse study to be $q_1^* = 6.5 \times 10^{-2}$ (ppm). In addition to a 95% upper-limit incremental unit risk, a measure of carcinogenic potency was determined for 1,3-butadiene. Among the 54

chemicals that the CAG has evaluated as suspect carcinogens, 1,3-butadiene ranks fairly low in potency, placing at the top of the fourth quartile.

2. INTRODUCTION

1,3-Butadiene (CAS No. 106-99-00) is a colorless gas produced as an ethylene coproduct, by oxidative dehydrogenation of n-butenes, or by dehydrogenation of n-butanes. In 1977, between 2.1 and 7.3 billion pounds of 1,3-butadiene were produced or imported. 1,3-Butadiene ranked 36th in U.S. domestic chemical production in 1983. It is used as an intermediate in the production of polymers, elastomers, and other chemicals. The major use of 1,3-butadiene is in the manufacture of styrene-butadiene rubber (synthetic rubber). In addition, 1,3-butadiene is used as an intermediate to produce a variety of industrial chemicals, including the fungicides, captan and captofol. The U.S. Food and Drug Administration has approved 1,3-butadiene for use in the production of adhesives used in certain types of food containers.

Although 1,3-butadiene has been found in U.S. drinking water, it is primarily an air contaminant. It has been detected in cigarette smoke, incineration products of fossil fuels, gasoline vapor, and automotive exhaust. Concentrations ranging from 1 to 5 ppb have been detected in urban air. Higher concentrations, up to 45 ppm, have been reported in air samples and factory emissions at petrochemical plants.

Approximately 62,000 workers are exposed annually to 1,3-butadiene. Occupational exposure to 1,3-butadiene occurs mainly through inhalation and, to a lesser extent, by dermal contact. Most occupational exposures occur in plants manufacturing 1,3-butadiene or using it to produce polymers or elastomers. The current permissible exposure limit of 1,000 ppm as an 8-hour time-weighted average was adopted by the Occupational Safety and Health Administration from the 1968 Threshold Limit Values (TLV) set by the American Conference of Governmental Industrial Hygienists (ACGIH). In 1983, the ACGIH, based on the findings

in experimental animals, gave notice of intention to list the material as an industrial substance suspected of carcinogenic potential for man and to remove the TLV. The National Institute for Occupational Safety and Health (NIOSH), considering the same animal information, issued a Current Intelligence Bulletin recommending that the occupational exposure be reduced to the lowest feasible level because of the potential for the compound to produce cancer.

The National Toxicology Program is currently undertaking a series of investigations of 1,3-butadiene. These studies will provide information on the pharmacokinetics and toxicity of the chemical. The reason for the apparent differences in sensitivity between the rat and mouse are to be investigated. In addition, the carcinogenic response at lower airborne concentrations may be established.

3. MUTAGENICITY OF 1,3-BUTADIENE AND ITS REACTIVE METABOLITES

This chapter deals with the mutagenicity of 1,3-butadiene, which is a gas at room temperature, and also includes a discussion of the metabolism of 1,3-butadiene and the mutagenicity of its reactive metabolites (3,4-epoxybutene and 1,2:3,4-diepoxybutane). The available evidence suggests that 1,3-butadiene is mutagenic by virtue of its metabolism to mutagenic intermediates.

3.1. MUTAGENICITY OF 1,3-BUTADIENE

1,3-Butadiene was tested for its mutagenic potential in the Salmonella typhimurium histidine reversion assay by de Meester et al. (1980). The sample of 1,3-butadiene studied was 99.5% pure and was obtained from Matheson Gas Products, Belgium. Salmonella strain TA1530 was exposed to 1,3-butadiene for 24 hours at 0, 4, 8, 16, 24, and 32% (vol/vol) in controlled atmospheres in desiccators. In the absence of S9 mix or in the presence of S9 prepared from untreated rats, no increase in the revertant frequency was observed. However, when the bacteria were exposed to 1,3-butadiene in the presence of S9 mix prepared from phenobarbitone or Aroclor 1254-pretreated rats, mutagenic activity was observed. The number of histidine revertants increased in a dose-related fashion from 17 per plate in the absence of 1,3-butadiene up to 255 per plate at 16% (vol/vol) 1,3-butadiene. These results suggest that 1,3-butadiene itself is not a mutagen, and that it is metabolized into mutagenic metabolic intermediates that cause base-pair substitutions.

Data suggesting that the mutagenic metabolites are volatile were also reported by de Meester et al. (1980). When plates containing bacteria and phenobarbitone or Aroclor-induced S9 mix were coincubated in 4 to 32% 1,3-butadiene atmospheres with plates containing only the bacteria, mutant colonies appeared on both sets of plates. The number of mutant colonies was pro-

portional to the level of 1,3-butadiene in the desiccators up to 16%.

A small study by Poncelet et al. (1980) supports the conclusion of de Meester et al. (1980) on the mutagenic potential of 1,3-butadiene in Salmonella strain TA1530. Mutagenic effects were observed when the assays were performed in a 16% gaseous atmosphere of 1,3-butadiene in the presence of Aroclor-induced S9 mix. When the bacteria were exposed to 1,3-butadiene under the conditions of the plate incorporation method or preincubation in liquid medium, mutagenicity was not observed. The 1,3-butadiene sample was 99.5% pure and was obtained from Matheson Gas Products, Belgium.

In summary, the two available studies suggest that 1,3-butadiene is a promutagen in bacteria; its mutagenicity depends on metabolic activation by a chemically induced S9 mix. No animal studies have been reported.

3.2. METABOLISM OF 1,3-BUTADIENE AND REACTION OF METABOLITES WITH DNA

As described in the previous section, 1,3-butadiene itself does not appear to be mutagenic. Mutagenic activity is observed only when 1,3-butadiene has been metabolized to reactive intermediates. A scheme for the metabolism of 1,3-butadiene and the DNA binding potential of the probable metabolites are briefly discussed in this section.

Malvoisin et al. (1979) and Malvoisin and Roberfroid (1982) studied the metabolism of 1,3-butadiene in vitro using rat liver microsomes. They reported that the metabolism proceeds via a mixed-function oxidase-catalyzed oxidation to 3,4-epoxybutene, and they suggest that this compound is subsequently metabolized to 1,2:3,4-diepoxybutane (diepoxybutane) and 3-butene-1,2-diol (Figure 1). Both 3,4-epoxybutene and diepoxybutane are probably reactive intermediates, whereas 3-butene-1,2-diol and its metabolite 3,4-epoxy-1,2-butanediol are probably detoxification products. Preliminary dence in rats suggests that 1,3-butadiene is metabolized to 3,4-epoxybutene in vivo (Bolt et al., 1983). Both

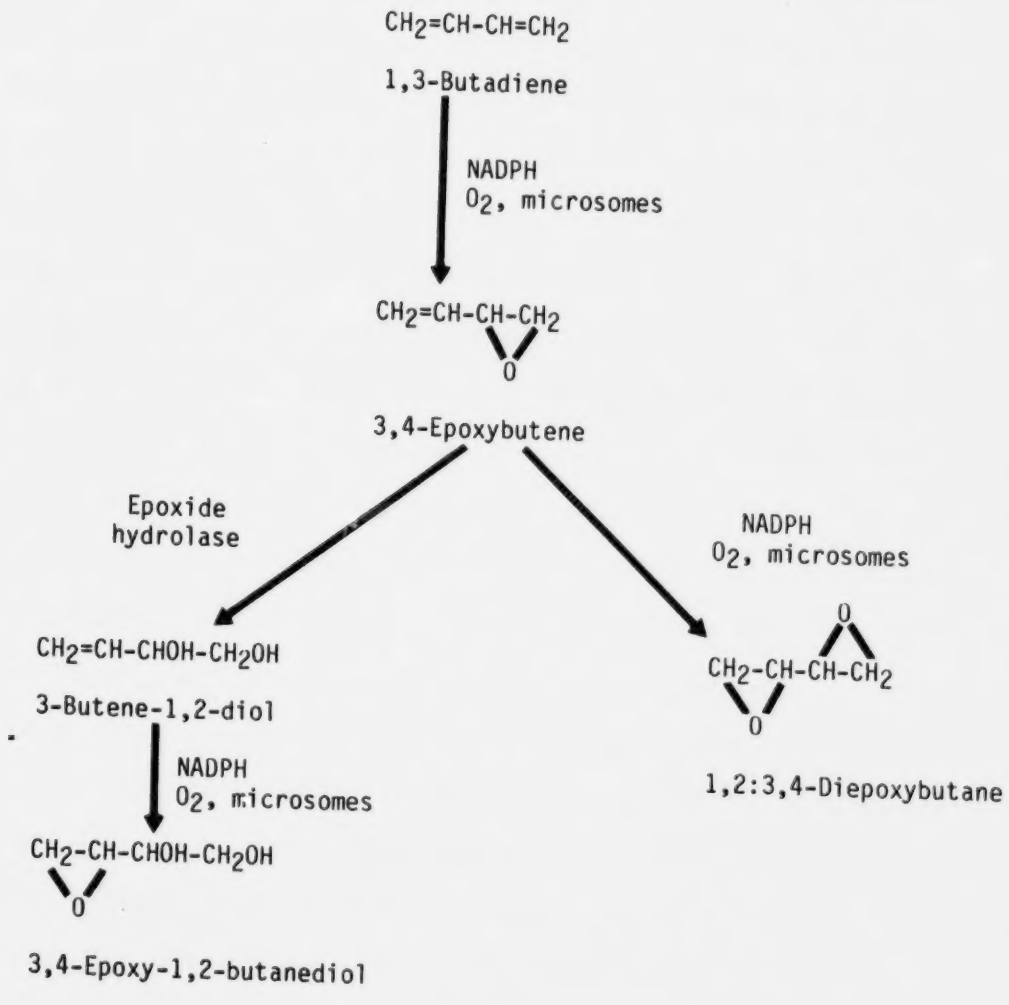

Figure 1. A hypothetical scheme for the metabolism of 1,3-butadiene.

SOURCE: Malvoisin and Roberfroid, 1982.

3,4-epoxybutene and diepoxybutane are mutagenic, as described more fully below. No information is available on the mutagenicity of 3-butene-1,2-diol and 3,4-epoxy-1,2-butanediol.

The alkylating ability of the two reactive metabolites of 1,3-butadiene (3,4-epoxybutene and diepoxybutane) has been investigated, each in a single study. Hemminki et al. (1980) found that 3,4-epoxybutene alkylated 4-(p-nitrobenzyl)-pyridine (NBP) and deoxyguanosine, which are nucleophiles that were used as models for DNA. The NBP reaction was carried out at 37°C using the test compound at 0.286 μM. The deoxyguanosine reaction was carried out at 37°C using the test compound at 0.1 M. In both cases, aliquots of the reaction mixture were assayed for alkylation at 0 minutes, 20 minutes, 1 hour, 3 hours, and 5 hours. The reaction rates were determined from the initial rates. The results were calculated using epichlorohydrin as a reference. 3,4-Epoxybutene alkylated NBP and deoxyguanosine at rates that were 31% and 14%, respectively, of that of epichlorohydrin. The alkylation activity correlated with mutagenicity in Escherichia coli WP2 uvrA, as described in the next section.

Lawley and Brookes (1967) reported that diepoxybutane reacts with DNA in a manner typical of bifunctional alkylating agents and causes interstrand cross-linking in DNA. Salmon sperm DNA was dissolved in 0.5 mM sodium citrate at 2 mg/mL (5.4 mM DNA phosphorus) and 25 mL was treated with redistilled diepoxybutane (2.4 mg/mL, 28 mM) at 37°C. Samples were withdrawn after 2, 5, 7, 24, 48, 72, 120, 168, and 193 hours. Ultraviolet spectroscopy was used to measure the reaction of diepoxybutane with DNA. At 37°C, diepoxybutane reacted with DNA slowly, as shown by changes in ultraviolet absorption of the reaction mixtures.

The extent of interstrand cross-linking (i.e., covalent linkage of the two DNA strands by the reaction of diepoxybutane with a nucleotide base in each DNA strand) was studied by measuring the reversible denaturation (renaturation)

of diepoxybutane-treated DNA. In this experiment, diepoxybutane-treated DNA was first incubated at 60°C for various time periods and then rapidly cooled. At 60°C, untreated DNA denatures when it is dissolved in a solution of low ionic strength (i.e., the two strands separate). When cooled, the DNA renatures (i.e., the two strands rejoin to reform the typical double-stranded DNA molecule). Diepoxybutane-treated DNA renatured to a greater extent than did normal untreated DNA, suggesting that diepoxybutane-treated DNA was cross-linked by a diepoxybutane bridge covalently joining the two DNA strands.

In summary, the above two studies indicate that 3,4-epoxybutene and diepoxybutane can alkylate DNA and that diepoxybutane causes interstrand cross-links in DNA.

3.3. MUTAGENICITY OF 3,4-EPOXYBUTENE

The mutagenic potential of 3,4-epoxybutene was studied in the fluctuation test with Klebsiella pneumoniae as the test organism (Voogd et al., 1981). The compound was obtained from K and N (ICN, Life Sciences Division, New York), was analytical grade, and was not further purified. The chemical was dissolved and diluted in dimethylsulfoxide and subsequently added to broth which was inoculated with the test organism. The genetic characteristic studied was streptomycin resistance. The average spontaneous mutation rate for streptomycin resistance was 0.1676×10^{-9}. Triplicate experiments were averaged, and the results were expressed as the quotient of the observed and spontaneous mutation rates. At 1 and 2 mM 3,4-epoxybutene, the quotients were 1.7 and 2.5, respectively, providing suggestive evidence of a dose-related positive response.

Besides studying the alkylating activity of 3,4-epoxybutene, Hemminki et al. (1980) studied its mutagenicity in a tryptophan-requiring strain of E. coli. The concentrations of 3,4-epoxybutene used were not specified but were based on toxicity determinations. Bacteria of strain WP2 uvrA were incubated

with the chemical for 18 hours at 37°C, after which aliquots were plated onto minimal agar to detect reversion to tryptophan prototrophy and onto nutrient agar containing tryptophan to determine the total number of cells. Although the study suggests that 3,4-epoxybutene is mutagenic in E. coli WP2 uvrA, there was no indication of a dose-related response; the result for only one dose was reported and that dose was unspecified. Although this study is of limited use for risk assessment purposes, it supports the study of Voogd et al. (1981) in suggesting that 3,4-epoxybutene is mutagenic in bacteria.

3.4. GENOTOXICITY OF 1,2:3,4-DIEPOXYBUTANE

3.4.1. Studies in Bacteria

Voogd et al. (1981) investigated the mutagenic potential of diepoxybutane in K. pneumoniae in the same paper cited previously for the mutagenicity of 3,4-epoxybutene. The source of the diepoxybutane was Merck (Darmstadt, F.R.G.); it was of analytical grade and was not further purified. At an equal chemical concentration (1 mM), diepoxybutane was approximately 16 times as mutagenic as 3,4-epoxybutene. The quotients of observed and spontaneous rates of mutation to streptomycin resistance for 0.05, 0.1, 0.2, 0.5, and 1 mM diepoxybutane were 1.7, 3.1, 6.2, 15.7, and 27, respectively. These results clearly indicate that diepoxybutane is mutagenic in K. pneumoniae and provide strong evidence of a dose-related response as well.

Diepoxybutane is also mutagenic in the S. typhimurium histidine reversion assay (Wade et al., 1979). Plate incorporation assays were performed with strains TA98 and TA100, and averages of two to five determinations were reported. At 0.02, 0.10, and 0.50 mg of diepoxybutane per plate, there were 196, 325, and 663 revertant colonies per plate with strain TA100 and 32, 22, and 29 revertant colonies per plate with strain TA98. These results suggest that diepoxybutane is a base-pair substitution mutagen in S. typhimurium because it produced a

dose-related positive response in strain TA100. Although strain TA100 is not specific for mutagens that induce base-pair substitutions, it responds well to such mutagens, and the result in strain TA98, which detects many frameshift mutagens, was negative.

3.4.2. Studies in Fungi

The mutagenic potential of diepoxybutane in the yeast Saccharomyces cerevisiae was studied by Olszewska and Kilbey (1975). They used a diploid yeast strain that is homozygous for the ilv mutation and therefore requires isoleucine and valine to grow. Kinetic studies of the induction of revertants were carried out by treating cells for various times with 0.1 M diepoxybutane at 25°C. About 1.2×10^6 to 1.5×10^6 cells were plated per petri dish. Diepoxybutane induced an increase in ilv reversions with increasing time of exposure up to 20 minutes. At 5, 10, 15, and 20 minutes, the number of ilv^+ revertants per 10^6 cells was about 3, 10, 20, and 38, respectively. Reversion of the ilv mutation indicates that diepoxybutane induces point mutations in yeast.

Zaborowska et al. (1983) have shown that diepoxybutane induces mitotic crossing-over and mitotic gene conversion in the SBTD and D7 strains of S. cerevisiae. Stationary-phase cells were suspended in phosphate buffer at 2×10^8/mL. The cells were treated with 0.4% (vol/vol) diepoxybutane (Merck, purity not specified) at 30°C for 15, 30, and 45 minutes. The treatment was terminated by centrifuging and washing cells twice with buffer.

The results of these experiments are shown in Table 1. The frequency of mitotic crossing-over in the SBTD strain was dose (exposure time) related. Dose-dependence of mitotic crossing-over in strain D7 is less clear. Dose-related increases in mitotic gene conversion were obtained in both strains. Taken together, these results indicate that diepoxybutane is recombinogenic in yeast, and recombinogenicity is an indication of DNA damage.

TABLE 1. INDUCTION OF MITOTIC GENE CONVERSION AND MITOTIC CROSSING-OVER IN SBTD AND D7 STRAINS OF *S. cerevisiae* BY DIEPOXYBUTANE

Exposure to 0.4% diepoxybutane (min)	Survival	Mitotic crossovers (%)	Convertants[a]
SBTD strain			
0	100	0	0.7
15	100	1.4	86.6
30	93.2	2.8	167.1
45	41.3	6.1	515.2
D7 strain			
0	100	0	0
15	100	1.5	40.4
30	78.4	1.7	278.0

[a]Convertants calculated per 10^7 survivors in the SBTD strain and per 10^6 survivors in the D7 strain.

SOURCE: Zaborowska et al., 1983.

Luker and Kilbey (1982) reported that diepoxybutane causes point mutations and multigenic deletions in Neurospora crassa. They developed a Neurospora heterokaryon in which both point mutations and deletions can be detected by the use of selective techniques. Point mutations were scored by reversion to adenine independence. Deletions were detected by first assaying for resistance to p-fluorophenylalanine (pFPA) and then testing for sensitivity to cycloheximide. These two genes are closely linked on chromosome V.

Information on the source and purity of the sample of diepoxybutane studied was not provided. Suspensions of Neurospora conidia were treated for various times with 0.1 M diepoxybutane in 0.067 M phosphate buffer (pH 7.0) at 27°C. The treatments were terminated by filtering off the mutagenic solution and washing the cells with 10% sodium thiosulfate solution. Diepoxybutane induced dose (exposure time) related increases in both adenine reversions and pFPA resistance, as shown in Table 2. The results shown in Table 3 suggest that about one-fourth of the pFPA-resistant mutants were deletions rather than point mutations because pFPA resistance was associated with sensitivity to cycloheximide 26.3% of the time. The evidence therefore shows that diepoxybutane is both mutagenic and clastogenic in Neurospora.

3.4.3. Studies in Mammalian Cells

The results of a study by Dean and Hodson-Walker (1979) suggest that diepoxybutane is a powerful clastogen in cultured rat liver epithelial cells. The sample of diepoxybutane studied was obtained from Fluka A.G., Switzerland. Its purity was not described. The epithelial-like cell line used, designated RL_1, is neardiploid, having a chromosome number of 44 or 45 (compared to the normal number of 42 in the rat karyotype). The appropriate concentrations of diepoxybutane for testing were determined from cytotoxicity studies. Because diepoxybutane is volatile, sealed flask cultures of the rat liver cells were

TABLE 2. INDUCTION OF ADENINE REVERSIONS AND pFPA RESISTANCE IN N. crassa BY 0.1 M DIEPOXYBUTANE

Treatment (min)	Survival (%)	Heterokaryotic conidia screened ($\times 10^6$) for		Number of mutants scored		Mutation frequency $\times 10^{-6}$	
		ad^+	pFPA resistant	ad^+	fpr^+	ad^+	fpr^r
0	100.0	15.64	4.17	5	2	0.32	0.48
10	78.1	6.90	1.38	22	12	3.19	8.70
20	60.4	5.54	1.13	34	21	6.03	18.58
30	40.8	2.53	0.51	53	21	20.95	41.18

SOURCE: Luker and Kilbey, 1982.

TABLE 3. ANALYSIS OF $pFPA^r$ MUTANTS AS PUTATIVE DELETIONS

Treatment with 0.1 M diepoxybutane (min)	Number of pFPA-resistant mutants tested	Number acquiring sensitivity to cycloheximide	Putative deletions (%)
10	12	5	42
15	7	2	29
20	41	10	24
30	94	21	22
45	25	10	40
60	11	2	18
Total	190	50	26.3

SOURCE: Luker and Kilbey, 1982.

used. The cell cultures were exposed to diepoxybutane for 24 hours, and colcemid at 0.3 μg/mL was added 2 hours before harvesting the cells with 0.25% trypsin. Distilled water was added to the harvested cells to produce hypotonic conditions. The cells were fixed in methanol/acetic acid (3:1). Chromosome preparations were made by air-drying the cells on microscope slides and staining with Giemsa. The slides were randomly coded, and 100 metaphases from each slide were analyzed for structural chromosome changes. Diepoxybutane was a powerful clastogenic agent, producing chromosome damage in a dose-related manner (Table 4).

Perry and Evans (1975) reported that exposure of cultured Chinese hamster ovary cells to diepoxybutane resulted in a dose-related induction in sister chromatid exchanges (SCEs). SCE involves the reciprocal exchange of DNA segments between sister chromatids and is considered an indication of DNA damage. The cells were treated with 10 μM bromodeoxyuridene and 0.3 μM or 3 μM diepoxybutane for two cycles of DNA replication before treatment with colcemid (2 hours at 0.2 μM), collection by mitotic shakeoff, pretreatment with 75 mM KCl, and fixation in methanol/acetic acid (3:1). Twenty mitotic cells were scored for each dose. Total SCEs at 0, 0.3, and 3 μM diepoxybutane were 244, 403, and 1818, respectively.

3.4.4. In vivo Studies

Studies of the mutagenic potential of diepoxybutane in whole animals have been carried out in mice and Drosophila melanogaster (fruit flies).

Conner et al. (1983) studied the ability of diepoxybutane to induce in vivo SCE in bone marrow, alveolar macrophages, and regenerating liver cells in mice. The sample of diepoxybutane studied was 97% pure and was obtained from Aldrich Chemical Co. It was dissolved in phosphate-buffered saline just prior to injection. The dose-response studies were performed in three intact and three partially hepatectomized Swiss Webster mice (mean weight of 27 g).

TABLE 4. EFFECTS OF DIEPOXYBUTANE ON CHROMOSOMES OF RAT LIVER CELLS

Diepoxybutane (µg/mL)	Number of cells analyzed	Chromatid gaps (%)	Chromatid deletions (%)	Chromatid exchanges (%)	Chromosome aberrations (%)
0	269	2.6	0.4	0	0.4
0.1	117	11.1	4.3	8.5	0.9
0.5	24	8.3	20.8	33.3	0
1.0	29	0	0	3.4	0

SOURCE: Dean and Hodson-Walker, 1979.

Diepoxybutane (10-291 μmol/kg) was injected intraperitoneally just prior to bromodeoxyuridine infusion (10 mg/mL; intravenous flow rate of 3.6 mL/24 hours). Colchicine (3.3 mg/kg) was then injected intraperitoneally. Bone marrow and alveolar macrophage cells from intact mice and regenerating liver cells from hepatectomized mice were harvested 4 hours later. As shown in Table 5, diepoxybutane produced similar dose-dependent responses for SCE in bone marrow, alveolar macrophages, and regenerating liver cells. Conner et al. (1983) also reported that the DNA lesions did not persist beyond one cell cycle. These results show that diepoxybutane is very effective in producing a dose-dependent SCE response, but that the initially induced lesions disappear in subsequent division cycles.

A positive response for diepoxybutane in the sex-linked recessive lethal test in Drosophila was reported in two studies from the same laboratory. The sex-linked recessive lethal test is a useful assay for testing the mutagenic potential of chemicals in the germ line of an intact animal. In the first study, Sankaranarayanan (1983) exposed wild-type Berlin-K adult 3 or 4-day-old male flies to 2 mM diepoxybutane in 5% sucrose by feeding for 48 hours. The diepoxybutane sample studied was obtained from Fluka, A.G., Switzerland. Information on its purity was not reported. The males were mated to Oster females to raise three successive 2-day broods (A, B, and C), and the F_1 female progeny were used in the tests for lethals. Brood A tests mature spermatozoa, brood B tests late spermatids, and brood C tests early spermatids. The results are shown in Table 6. A concurrent no-exposure control was not done in this study or in the subsequent study described below. However, a historical control value for Drosophila of 0.18% has been established in the same laboratory from the evaluation of 13,151 chromosomes (Vogel, 1976). The results suggest that diepoxybutane is a strong inducer of sex-linked recessive lethal mutations

TABLE 5. SCE FREQUENCIES INDUCED IN BONE MARROW, ALVEOLAR MACROPHAGES, AND REGENERATING LIVER CELLS OF SWISS WEBSTER MICE FOLLOWING INJECTION OF DIEPOXYBUTANE

Diepoxybutane (μ mol/kg)	Bone marrow		Alveolar macrophages		Regenerating liver	
	A[a]	B[b]	A	B	A	B
Hepatectomized mice						
0	4.2 ± 0.6	66	3.5 ± 0.6	77	3.7 ± 0.9	80
10	7.2 ± 0.9	63	7.9 ± 0.4	71	7.0 ± 1.4	73
39	8.1 ± 1.4	72	9.8 ± 1.0	70	11.9 ± 2.6	69
97	10.9 ± 1.5	63	13.4 ± 3.4	75	14.9 ± 4.0	69
193	22.3 ± 3.5	44	23.6 ± 4.5	59	28.9 ± 6.1	43
291	32.0 ± 6.6	22	30.4 ± 4.9	23	31.1 ± 5.9	29
Intact mice						
0	3.0 ± 0.8	64	3.6 ± 0.5	63		
10	5.4 ± 0.6	58	6.7 ± 1.2	54		
39	8.8 ± 0.8	63	10.2 ± 0.3	57		
97	9.7 ± 1.5	63	12.8 ± 2.3	62		
193	14.6 ± 2.1	43	17.1 ± 2.2	41		
291	27.3 ± 3.7	46	28.6 ± 3.8	42		

[a]Mean SCE/cell ± S.D. of three mice at each dose. Individual animal means were calculated from SCEs scored in 20 cells of each type.
[b]Mean number of second division cells observed in 100 consecutive metaphases.

SOURCE: Conner et al., 1983.

TABLE 6. FREQUENCIES OF SEX-LINKED RECESSIVE LETHALS INDUCED BY 2 mM DIEPOXYBUTANE IN POSTMEIOTIC MALE GERM CELLS OF *Drosophila*

Experimental strain	Brood[a]	Number of chromosomes	Lethals	
			Number	%
Berlin-K[b]	A	800	42	6.5
	B	914	32	4.8
	C	840	30	4.6
Canton-S[c]				
Experiment 1	A	934	88	9.4
	B	949	68	7.2
	C	960	66	6.9
Experiment 2	A	938	64	6.8
	B	951	54	5.7
	C	350	14	4.0
Ebony[c]				
Experiment 1	A	932	88	9.4
	B	912	65	7.1
	C	925	56	6.1
Experiment 2	A	876	57	6.5
	B	924	41	4.4
	C	885	33	3.7

[a]Brood A corresponds to treatment of mature spermatozoa; Brood B corresponds to late spermatids; and Brood C corresponds to early spermatids.
[b]Taken from Sankaranarayanan, 1983.
[c]Taken from Sankaranarayanan et al., 1983.

(6.5%, 4.8%, and 4.6% compared to the historical control value of 0.18%). The results also indicate that mature spermatozoa (brood A) respond with higher frequencies of recessive lethals than late and early spermatids (broods B and C).

Similar positive results (Table 6) were obtained in a later study in Drosophila (Sankaranarayanan et al., 1983). The experimental details in this study were identical to those described above, except that Canton-S and ebony males were exposed to diepoxybutane and mated to Muller-5 females. Accordingly, the strong mutagenic response appears to be independent of the strains employed. The strongly positive results in the sex-linked recessive lethal test provide clear evidence that diepoxybutane reaches the gonads and is strongly mutagenic in germ cells of Drosophila.

There is evidence that diepoxybutane induces chromosome damage in germ cells of Drosophila (Zimmering, 1983). Treated males carried an X chromosome in the form of a closed ring and a Y chromosome carrying dominant markers, one at the end of long arm of the Y and one at the end of the short arm. The males were permitted to feed on a solution of 1.25 mM diepoxybutane in 5% sucrose for 24 hours and then mated with repair-proficient (ordinary) females or to repair-deficient females. There was no evidence of toxicity in the treated males. The F_1 offspring were scored for complete loss of the X or Y chromosomes (in ring-X males, virtually all complete loss is attributable to ring loss) and for partial loss of the Y chromosome, indicated by the loss of one but not both of the Y chromosome markers. Complete loss indicates chromosome breakage and/or sister chromatid exchange. Partial loss of the Y chromosome is a consequence of breakage. Results shown in Table 7 provide evidence of a relatively strong effect on complete loss (5-6%) and a significant increase in partial loss which is most apparent from matings with the repair-deficient females (approx. 3%).

In summary, the results of the Drosophila experiments assaying for sex-

TABLE 7. CHROMOSOME LOSS IN *Drosophila* FROM MATINGS OF MALES WITH REPAIR-PROFICIENT (RP) AND REPAIR-DEFICIENT (RD) FEMALES

Series	Female	N	Complete loss	Partial loss	Percent induced: Complete loss	Percent induced: Partial loss
Control	RP	8551	51	0		
Treated		7390	515	8	6.37	0.11
Control	RD	3178	30	2		
Treated		1285	82	39	5.44	2.97

All induced frequencies are statistically significant at or below the 0.01 level. The repair-deficient mutant was *mei-9*^{a}, which is deficient in excision repair.

SOURCE: Zimmering, 1983.

linked recessive lethals and chromosome loss provide strong evidence that diepoxybutane is a mutagenic and chromosome damaging agent in germ cells of Drosophila. In addition, the results of the SCE assay in mice suggest that diepoxybutane is a DNA damaging agent in mice.

3.5. SUMMARY OF MUTAGENICITY STUDIES

The available information on the mutagenicity of 1,3-butadiene is quite limited in that only two studies have been reported. Both studies, however, indicate that 1,3-butadiene is a mutagen in S. typhimurium. The mutagenicity is observed only in the presence of a liver S9 metabolic activation system. No whole animal studies have been reported. These results suggest that 1,3-butadiene is a promutagen in bacteria (i.e., its mutagenicity depends on metabolic activation).

Mutagenic metabolites of 1,3-butadiene include 3,4-epoxybutene and diepoxybutane. 3,4-Epoxybutene is a monofunctional alkylating agent and is a direct-acting mutagen in bacteria; it has been tested in K. pneumoniae and E. coli.

Diepoxybutane is a bifunctional alkylating agent and as such it can form cross-links between the two strands of DNA. It is mutagenic in bacteria (K. pneumoniae and S. typhimurium), fungi (yeast and Neurospora), and the germ cells of Drosophila. It also induces DNA damage in cultured hamster cells and in mice, is clastogenic in fungi and cultured rat cells, and produces chromosome damage/breakage in Drosophila germ cells. Therefore, there is strong evidence that diepoxybutane is a mutagen/clastogen in microbes and animals.

In summary, the weight of the available evidence suggests that 1,3-butadiene is a mutagen by virtue of its metabolism to mutagenic intermediates, particularly diepoxybutane.

4. CARCINOGENICITY

The purpose of this chapter is to provide an evaluation of the likelihood that 1,3-butadiene is a human carcinogen and, on the assumption that it is a human carcinogen, to provide a basis for estimating its public health impact and evaluating its potency in relation to other carcinogens. The evaluation of carcinogenicity depends heavily on animal bioassays and epidemiologic evidence. However, additional factors, including mutagenicity, pharmacokinetics, and other toxicological characteristics have an important bearing on both the qualitative and quantitative assessment of carcinogenicity. This section presents an evaluation of the animal bioassays, the epidemiologic evidence, and the quantitative aspects of risk assessment.

4.1. TOXICOLOGY AND PHARMACOKINETICS

Information on the toxicity of 1,3-butadiene resulting from acute exposure is limited. The median lethal concentrations for mice and rats of 1,3-butadiene for periods of exposure ranging from 2 to 4 hours are above 100,000 ppm. The oral LD_{50} values for rats and mice are 5.48 g/kg and 3.21 g/kg, respectively. The major acute toxic effects are irritation of the respiratory tract, mucous membranes, and eyes, and narcosis (NTP, 1984).

A teratogenicity study sponsored by the International Institute of Synthetic Rubber Producers, Inc., was conducted at Hazleton Laboratories Europe, Ltd. (1981b) in England. Pregnant female Charles River CD rats (Sprague-Dawley), obtained from Charles River Ltd., were exposed to concentrations of 200, 1,000, and 8,000 ppm of 1,3-butadiene, 6 hours/day, on days 6-15 of gestation. The rats were observed daily and weighed at intervals during the study. On day 20 of gestation the females were killed, necropsied, and the uterine contents inspected. One-third of each litter was examined for visceral abnormalities,

and the remainder were examined for skeletal anomalies. There were 24 female rats assigned to each treatment group, and 40 were assigned to the control group which was exposed to filtered air.

The maternal animals were not affected by exposure to the 1,3-butadiene except for reduced weight gain in those exposed to 8,000 ppm. The authors concluded, as a result of the maternal toxicity, that there was embryonic growth retardation and slight embryolethality among all dose groups, and that the magnitude of the effect was dose-related. The relationship between maternal toxicity and the fetal effects was a subjective judgment and not experimentally established. The authors further concluded that at the highest dose there was an indication of teratogenicity based on the presence of major fetal defects. There was a significant increase in "minor" defects at the lowest airborne concentration tested (200 ppm). Whether this represents a qualitative change in the dose-response or is due to other factors, such as maternal toxicity, cannot be determined from the information available. In an earlier but inadequately reported study (Carpenter et al., 1944), decreases in litter size were reported in rats exposed to 6,700 and 2,300 ppm, but not at 600 ppm.

As detailed in the preceding section, *in vitro* studies have indicated that 1,3-butadiene is metabolized in liver microsomes by P-450-dependent mixed-function oxidases. The biotransformation, although only partially confirmed by *in vivo* experiments in rats (Bolt et al., 1983), could lead to the formation of 3,4-epoxybutene, then to 1,2:3,4-diepoxybutane (diepoxybutane) or to 3-butene-1,2-diol, then to 3,4-epoxy-1,2-butanediol, followed by the formation of erythritol (Malvoisin and Roberfroid, 1982). In addition to being mutagenic, diepoxybutane is classified, in the Third Annual Report on Carcinogens, as a substance that may be reasonably anticipated to be a carcinogen. This determination was in turn based on the International Agency for Research on Cancer

(IARC) finding of sufficient evidence for carcinogenicity in experimental animals. The studies underlying these determinations show a carcinogenic response following skin application in mice and the production of local cancer in mice and rats by subcutaneous injection.

Information concerning the pharmacokinetics of 1,3-butadiene is limited. Carpenter et al. (1944) determined that blood concentrations in the femoral artery and in the femoral vein of rabbits at nine minutes after exposure to an airborne concentration of 250,000 ppm were 0.26 mg/mL and 0.18 mg/mL, respectively. Rats exposed to 1,3-butadiene for 2 hours at an airborne concentration of 130,000 ppm had the highest concentrations of the chemical in perirenal fat (152 mg%); lower concentrations (36-51 mg%) were found in the liver, brain, spleen, and kidney. Ninety minutes after exposure to 130,000 ppm for one hour the tissue concentrations were minimal (Shugaev, 1969).

Preliminary results from further investigations by NTP (personal communication, 1985) indicated that following intraperitoneal injection of radiolabeled 1,3-butadiene, male B6C3F1 mice exhale most of the dose unchanged. Exhaled carbon dioxide was the next largest pool for the ^{14}C label. Lesser amounts were detected in the urine and feces. Little remained in the carcass 65 hours after intraperitoneal administration. Nose-only exposure of male mice at concentrations of 7.5, 97, 119, and 770 ppm for 6 hours did not alter the minute volume significantly. Although pulmonary absorption was lower than expected (3-11%), it was linearly related to the inhaled concentration. The urine was the major route of excretion of the absorbed 1,3-butadiene. The excretion of the metabolized products is linearly related to the inhaled concentration.

4.2. ANIMAL STUDIES

4.2.1. Chronic Toxicity Studies in Mice

A chronic toxicity and carcinogencity inhalation study of 1,3-butadiene in

B6C3F1 mice, sponsored by the NTP, was conducted at Battelle Pacific Northwest Laboratories. Preliminary inhalation toxicity studies in mice were used as a basis for dose selection for a chronic study. A 15-day study and a 14-week study were conducted at International Bio-Test Laboratories. In the 15-day study, weight loss at airborne concentrations of 1,250 ppm was observed. The mice exposed to 8,000 ppm, the highest airborne concentration, survived the exposure period. In the 14-week study, reduced body weight and death were observed among mice treated at 2,500 ppm or more. Necropsy findings were not reported (NTP, 1984).

The mice used in the chronic study were obtained from Charles River Laboratories and were exposed to graded concentrations of 625 and 1,250 ppm of 1,3-butadiene for 6 hours/day, 5 days/week. The exposures were conducted in dynamic negative-pressure exposure chambers, and the chamber concentrations were generated by mixing the test gas with filtered air. The chamber concentrations were measured 7 to 12 times a day for the first 150 days with a photoionization detector, and thereafter by gas chromatography. It was intended that the dimer (4-vinyl-1-cyclohexene) concentration in the test material before use should be controlled to less than 100 ppm. However, three cylinders with slightly more than 100 ppm of dimer were used because replacements were not available. The mice were 8 to 9 weeks of age when the exposures began, and were housed individually throughout the study. There were 50 mice per sex per dose group.

The mice were weighed weekly for the first 12 weeks of the study, and monthly thereafter. They were examined for subcutaneous masses beginning after the 12th week. Clinical signs were recorded weekly. Histopathological evaluation (32 tissues) was performed on all mice.

While the original plan was for this to be a 2-year study, all surviving

mice were killed after week 60-61 because of excessive deaths among the treated mice. Many of these deaths were caused primarily by the developing neoplasia. The survival (mice at risk; corrected for mice that were missing or were accidentally killed) at this early termination was as follows:

	Airborne concentration (ppm)		
	0	625	1,250
Males	49/49	11/50	7/46
Females	46/46	14/47	30/48

There were no increases in clinical signs that could be associated with exposure to 1,3-butadiene except those related to tumor development and death. The body weights were not affected by inhalation exposure to the test chemical.

There was a marked increase in the overall frequency of mice with primary tumors, as indicated below:

	Airborne concentration (ppm)		
	0	625	1,250
Males	10/50	44/50	40/50
Females	6/50	40/50	46/49

In addition to a marked increase in the number of animals with primary tumors, there was also an increase in the number of animals with multiple primary tumors. Among the tumor-bearing male mice, there were 11, 73, and 61 such tumors in the control, low-, and high-exposure groups, respectively. In the females, there were 6, 66, and 100 tumors in the tumor-bearing animals of the control, low-, and high-exposure groups, respectively.

The histopathologic evaluation indicated significant increases in tumors

of various types, as shown in Table 8. These tumors began to appear remarkably early in the course of the study. Lymphomas were diagnosed in mice dead at 22 and 20 weeks of exposure for males and females, respectively, of the high-exposure group. The first tumors of this type were found in low-dose mice at 24 and 29 weeks, respectively. Of the survivors, two males in the low-dose group and one in the high-dose group had lymphomas. In the females, one lymphoma was found among the surviving control mice, three in the low-dose group, and one in the high-dose group. Many of the early deaths were judged to be caused by this type of tumor.

The heart was the principal organ in which hemangiosarcomas occurred. The first hemangiosarcomas were diagnosed at 32 and 42 weeks in the low- and high-dose males and at 41 and 43 weeks among the females. The cardiac hemangiosarcomas may have caused some of the mice to die early. Atypical cardiac endothelial hyperplasia, a likely preneoplastic lesion, was not observed among the controls but was present in treated males (625 ppm - 10%, 1,250 ppm - 4%) and females (625 ppm - 10%, 1,250 ppm - 16%).

Alveolar/bronchiolar adenomas and carcinomas occurred (both separately and combined) at increased frequency in both male and female mice. In the high-dose groups the first such lesions appeared at week 42 for males and week 50 for females. Neoplastic changes in the lungs of the controls were not detected until the termination of the study. While neoplastic lesions of the nasal cavity were not found at any dose, there was an increase in nonneoplastic changes at the high dose. At 1,250 ppm, chronic inflammation of the nasal cavity (male, 33/50; female, 2/49), fibrosis (male, 35/50; female, 2/44), cartilaginous metaplasia (male, 16/50; female 1/49), osseous metaplasia (male, 11/50; female, 2/49), and atrophy of the sensory epithelium (male, 32/50) were observed. No nonneoplastic lesions of the nasal cavity were found in the controls. Huff et

TABLE 8. SUMMARY OF THE STATISTICALLY SIGNIFICANT INCIDENCE OF TUMORS IN MICE EXPOSED FOR 60-61 WEEKS TO 1,3-BUTADIENE

Tumor type and site	Sex	Airborne concentration (ppm) 0	625	1,250
Hemangiosarcomas (heart)	M	0/50 p=0.032[a]	16/49 p<0.001[b]	7/49 p=0.006[b]
	F	0/49 p=0.001[a]	11/48 p<0.001[b]	18/49 p<0.001[b]
Malignant lymphomas (hematopoietic system)	M	0/50 p<0.001[a]	23/50 p=0.001[b]	29/50 p=0.001[b]
	F	1/50 p<0.006[a]	10/49 p=0.003[b]	10/49 p=0.003[b]
Alveolar/bronchiolar adenoma	M	2/50 p=0.10[a]	12/49 p=0.003[b]	11/49 p=0.007[b]
	F	3/49 p<0.001[a]	9/48 p=0.056[b]	20/49 p<0.001[b]
adenoma/carcinoma	M	2/50 p<0.001[a]	14/49 p<0.001[b]	15/49 p<0.001[b]
	F	3/49 p<0.001[a]	12/48 p=0.010[b]	23/49 p<0.001[b]
Acinar cell carcinoma (mammary)	F	0/50 p=0.007[a]	2/49 p=0.242[b]	6/49 p=0.012[b]
Granulosa cell tumor or carcinoma (ovary)	F	0/49 p<0.001[a]	6/45 p=0.010[b]	13/48 p<0.001[b]
Forestomach (All papilloma and carcinoma)	M	0/49 p=0.354[a]	7/40 p=0.037[b]	1/44 p=0.473[b]
	F	0/49 p<0.001[a]	5/42 p=0.018[b]	10/49 p<0.001[b]
Hepatocellular adenoma	F	0/50 p=0.025[a]	1/47 p=0.485[b]	4/49 p=0.056[b]
adenoma/carcinoma	F	0/50 p=0.016[a]	2/47 p=0.232[b]	5/49 p=0.015[b]

[a]Cochran-Armitage Trend Test.
[b]Fisher Exact Test.

al. (1985) have suggested that the lack of neoplasms in the nasal cavity may reflect a requirement for biotransformation of 1,3-butadiene to a reactive epoxide intermediate.

Among the 10 control male mice with primary tumors, eight had hepatocellular adenomas and/or carcinomas. This type of tumor is normally observed among male mice of this strain in 2-year bioassays. It may be that the inclusion of mice with this type of tumor in considering the number of tumor-bearing animals tends to deemphasize the frequency of compound-induced neoplasia. On the other hand, among the females, the frequency of hepatocellular adenomas and/or carcinomas was increased. The occurrence of this type of tumor among females of this strain is more suggestive of adverse chemical-related effects. Among the male mice, there was a significant increase in liver necrosis at both doses. In the female mice, liver necrosis was significantly elevated only at the higher airborne concentration.

In addition to the neoplastic changes in the ovary and forestomach, ovarian atrophy and forestomach epithelial hyperplasia were elevated among the mice at both doses. Since Zymbal gland tumors have been reported in the chronic rat study to be discussed, it is worth noting that in this study, one also occurred in high-dose female mice and two occurred in high-dose male mice. This tumor is not normally found in control mice, even at the termination of a 2-year study. Testicular atrophy was observed in male mice at both dose levels; however, the increase in tumors of the testes that had occurred in the rats did not occur in the mice.

An audit of this chronic study was conducted by the NTP. Potential discrepancies that might have significantly influenced the interpretation of this study were resolved. The NTP considered that this study provided clear evidence of carcinogenicity, which is the highest classification in their system

of categorizing evidence of carcinogenicity.

4.2.2. Chronic Toxicity Studies in Rats

A 2-year chronic inhalation toxicity study using rats as the experimental animals was conducted by Hazleton Laboratories Europe, Ltd. (HLE, 1981a) in England. The study was sponsored by the International Institute of Synthetic Rubber Producers, Inc. The chronic study was preceded by a 3-month toxicity study. The airborne concentrations of 1,3-butadiene used in the 3-month study were 1,000, 2,000, 4,000, and 8,000 ppm. A control group was exposed to filtered air. No effects considered by the authors to be attributable to exposure to the test chemical were seen in growth rate, food consumption, hematology, blood biochemical investigations, or pathological evaluation. The only effect the investigators observed that might be related to 1,3-butadiene exposure was a moderate increase in salivation, particularly in female rats during the last 6 to 8 weeks of exposure at the higher airborne concentrations (Crouch et al., 1979).

For the chronic investigation (HLE, 1981a), Charles River CD rats (Sprague-Dawley rats obtained from Charles River Ltd.) were exposed to graded concentrations of 1,000 and 8,000 ppm of 1,3-butadiene. The exposures (6 hours/day, 5 days/week) for 111 and 105 weeks for males and females, respectively, were conducted in a dynamic negative-pressure exposure chamber. The chamber concentrations were generated by mixing the test gas with filtered air. The concencentrations were measured with an infrared gas analyzer. The dimer (4-vinyl-1-cyclohexene) concentrations in the test material before use were less than 1,000 ppm, but samples in the 700 to 800 ppm range were used, and the dimer concentration of these averaged 413 ppm. The rats were 4 1/2 weeks of age when the exposures began, and were housed five to a cage throughout the study. There were 110 rats per sex per dose group, and a similar number of rats exposed

to filtered air served as a control group.

The rats were weighed weekly and examined for subcutaneous masses and other clinical signs. Blood chemistries, hemograms, and urine analyses were evaluated at 3, 6, and 12 months. Neuromuscular function was evaluated periodically through week 77 of the study. Ten rats per sex per dose were killed and necropsied at week 52. Histopathological evaluations were performed on all rats from the high-dose group and the control group. Tissues from the low-dose group that were deemed to be of toxicological significance were also examined.

Variations in mean body weight suggested no consistent adverse effect. Review of the hemograms, blood chemistry, urine analysis, and behavioral testing was likewise not indicative of an adverse effect.

The clinical signs in the high-dose group, consisting of excessive secretion of the eyes and nose plus a slight ataxia, were observed between months 2 and 5. In addition, in the females of the treated groups subcutaneous masses appeared earlier and at a higher incidence than in the control group. A dose-related increase in liver weights was observed at the necropsy performed at 52 weeks and at the termination of the study. This could indicate that the chemical induces liver enzymes. Otherwise, no significant changes were noted at the 52-week kill.

In the control group, 45% of the males and 46% of the females survived until the end of the study (note: corrected for interim kill). In the high-dose group, survival was 32% and 24%, while in the low-dose group 50% and 32% survived. The decreased survival in the high-dose group was statistically significant.

Increased alveolar metaplasia and nephropathy were observed among males of the 8,000-ppm treatment groups at the termination of the study. Marked or severe nephropathy occurred in 27% of the male rats in the high-dose group, as compared with 9 to 10% in the control and the low-dose groups. The authors con-

sidered nephropathy to be the cause of some of the early deaths in this study. The frequency of metaplasia was 5/44 in the surviving male rats (8,000 ppm) as compared to 5/45 in the controls.

With regard to the carcinogenic potential of 1,3-butadiene, the authors of this study concluded that exposure of male and female rats under the conditions of this investigation was associated with significant increases in both common and uncommon tumors. Furthermore, they stated that the results of this 2-year inhalation study supported the premise that 1,3-butadiene is a suspect weak oncogen.

The incidence of selected neoplasms is shown in Table 9. In the females there was an increase in mammary carcinoma tumors (control - 8%, 1,000 ppm - 42%, 8,000 ppm - 38%). Also, in the females follicular thyroid adenomas were encountered more frequently among the treated females than among the controls (control - 0%, 1,000 ppm - 2%, 8,000 ppm - 8%). An increase in uterine/vaginal tumors (control - 0%, 1,000 ppm - 2%, 8,000 ppm - 8%) was also observed in the females. One female of the 8,000 - ppm exposure group had an uterine stromal tumor (unspecified).

In the males there was an increase in Leydig cell adenomas (control - 0%, 1,000 ppm - 2%, 8,000 ppm - 7%). A single Leydig cell tumor (unspecified) was observed in one male of each exposed group. Exocrine pancreatic adenomas were increased in the male rats of the high-dose group (control - 3%, 1,000 ppm - 1%, 8,000 ppm - 10%). One carcinoma was observed in this tissue in the males of the high-dose group.

Zymbal gland tumors were increased in the high-dose group, when male and female rats were combined. Except for these, the increase in tumors in this investigation was limited to tumors that developed in hormonal-dependent tissues.

TABLE 9. SUMMARY OF THE INCIDENCE OF TUMORS IN RATS EXPOSED TO 1,3-BUTADIENE (100 RATS PER SEX PER DOSE GROUP).

Tumor type and site	Sex	Airborne concentration (ppm) 0	1,000	8,000
Multiple mammary gland tumors	F	50 p<0.001[a]	79 p<0.001[b]	84 p<0.001[b]
Thyroid follicular (adenoma and carcinoma)	F	0 p<0.001[a]	4 p=0.06[b]	11 p<0.001[b]
Uterine cervical/ stromal sarcoma	F	1 p=0.115[a]	4 p=0.184[b]	5 p=0.106[b]
Leydig cell (adenoma and carcinoma)	M	0 p<0.003[a]	3 p=0.12[b]	8 p<0.001[b]
Pancreatic exocrine Carcinoma	M	0	0	1
Adenoma	M	3 p=0.019[a]	1 p=0.879[b]	10 p=0.041[b]
Zymbal gland (carcinoma)	M	0 p=0.384[a]	1 p=0.5[b]	1 p=0.5[b]
	F	0 p=0.037[a]	0	4 p=0.061[b]

[a]Cochran-Armitage Trend Test.
[b]Fisher Exact Test.

4.2.3. Summary of Chronic Toxicity Studies

The two chronic studies available at this time are compared in Table 10. The obvious difference is the marked sensitivity of the mice compared to the rats with regard to carcinogenic response. Some difference in this direction might be expected. For example, if the carcinogenic response is elicited by a metabolite, as has been suggested (de Meester et al., 1978, 1980), mice, because of their higher rate of metabolism, might be expected to yield a greater response than rats. The variation in housing during exposure (individually in the case of the mice versus in groups in the case of the rats), and the higher dimer content of the material to which the rats were exposed, might also be expected to contribute to the difference in the sensitivity of the mice. Among the other factors that might have led to this rather remarkable species differences are intralaboratory variations in dimer formation in the test atmospheres and variations in metabolite formation.

The tumors in the rats are largely characterized as occurring in hormonal-dependent tissues. Some suggestion of this is observed in the mice, but not to so great an extent. The occurrence of a similar array of tumors in the mice could have been prevented by the early deaths from more rapidly developing neoplasia. It is worth noting the Zymbal gland tumors did develop in both species, but were not as marked in the mice.

In the NTP mouse study, hemangiosarcomas of the heart, a very rare tumor, were markedly elevated in both groups exposed to 1,3-butadiene. The possible cardiac selectivity of 1,3-butadiene is further suggested by the presence of cardiac disease in two of the epidemiologic studies, as well as the occurrence of cardiac anomalies in the teratogenic investigations.

4.3. EPIDEMIOLOGIC STUDIES

The manufacture of styrene-butadiene rubber (SBR) involves the use of, and

TABLE 10. SIGNIFICANT EFFECTS OF EXPOSURE TO 1,3-BUTADIENE ON SPRAGUE-DAWLEY RATS AND B6C3F1 MICE IN INHALATION STUDIES

	Rats[a] (Hazleton Laboratories Europe, Ltd., 1981a)	
	1,000 ppm	8,000 ppm
Neoplasms:		
Male	Leydig cell adenoma[b]	Leydig cell adenoma[b] Pancreas: exocrine tumors[b] Brain: glioma
Female	Mammary gland: fibroadenoma/carcinoma[b] Thyroid: follicular cell adenoma[b] Uterus: stromal sarcoma[b]	Mammary gland: fibroadenoma/carcinoma[b] Thyroid: follicular cell adenoma[b] Uterus: stromal sarcoma[b] Zymbal gland: carcinoma[b]
Nonneoplastic lesions:		
Males		Increased focal alveolar epithelialization Nephropathy

	Mice[c] (National Toxicology Program, 1984)	
	625 ppm	1,250 ppm
Neoplasms:		
Males	Heart: hemangiosarcoma[b] Malignant lymphoma[b] Lung: alveolar/bronchiolar adenoma and carcinoma[b] Forestomach: papilloma[b] Preputial gland: squamous cell carcinoma[d] Brain: glioma[d]	Heart: hemangiosarcoma[b] Malignant lymphoma[b] Lung: alveolar/bronchiolar adenoma and carcinoma[b] Preputial gland: squamous cell carcinoma[d] Zymbal gland: carcinoma[d] Brain: glioma[d]
Females	Heart: hemangiosarcoma[b] Malignant lymphoma[b] Lung: alveolar/bronchiolar adenoma and carcinoma[b] Forestomach: papilloma[b] Ovary: granulosa cell tumor[b]	Heart: hemangiosarcoma[b] Malignant lymphoma[b] Lung: alveolar/bronchiolar adenoma and carcinoma[b] Forestomach: papilloma[b] Mammary gland: acinar cell carcinoma[b] Ovary granulosa cell tumor[b] Liver: hepatocellular adenoma or carcinoma (combined)[b]
Nonneoplastic lesions:		
Male	Forestomach: epithelial hyperplasia[b] Liver necrosis[b] Testicular atrophy[b]	Forestomach: epithelial hyperplasia[b] Liver necrosis[b] Nasal cavity lesions (chronic inflammation, fibrosis, cartilaginous metaplasia, osseous metaplasia, atrophy of sensory epithelium[b] Testicular atrophy[b]
Female	Liver necrosis[b] Forestomach: epithelial hyperplasia[b] Ovary: atrophy[b] Uterus: involution[b]	Forestomach: epithelial hyperplasia[b] Ovary: atrophy[b] Uterus: involution[b]

[a]Groups of 100 male and female Sprague-Dawley rats were exposed to air containing 0, 1,000 or 8,000 ppm 1,3-butadiene 6 hours/day, 5 days/week for 105 weeks (female), or 111 weeks (male); survival in dosed groups decreased.
[b]Statistically significant ($p < 0.05$)
[c]Groups of 50 male and female B6C3F1 mice were exposed to air containing 0, 625 or 1,250 ppm 1,3-butadiene 6 hour/day, 5 days/week for 60 week (male) or 61 weeks (female); survival in dosed groups decreased and was the reason for early termination.
[d]Considered uncommon at 60 weeks.

SOURCE: National Toxicology Program, 1984.

hence exposures to, several different chemicals. The two major components of SBR polymers are styrene and butadiene. In a typical recipe for the production of SBR, butadiene and styrene account for 26% and 9%, respectively, of the total ingredients. It should be pointed out that water accounts for 63% of the volume. At room temperature styrene is a clear, colorless liquid, while butadiene is a gas.

Two other agents, toluene and benzene, need to be considered, although they are not used directly in the manufacture of SBR. Toluene exposures result from its periodic use as a tank-cleaning agent; it may also exist as an impurity of styrene. Benzene exposures may occur as an impurity of styrene or toluene.

Occupational epidemiologic studies investigating the potential health hazards associated with the production of synthetic rubber have been very limited in number. Because styrene and butadiene are the two basic materials used in the manufacture of SBR, with benzene and toluene as byproducts, it is at best difficult to assess the singular contribution of each. Benzene exposure has been identified with excessive risk, particularly acute leukemia (Linet, 1985). Styrene also may be a leukemogen in humans (Ott et al., 1980; Lilis and Nicholson, 1976). Although many studies of rubber production workers have been conducted, only a few of those studies are relevant to butadiene exposure. Those studies, which are reviewed here, include studies of workers specifically identified as working in styrene-butadiene production or the manufacture of synthetic rubber. A study was also included if it was a preliminary study to one in which the workers were identified as SBR or synthetic rubber workers, or if it added to the interpretation of one of the studies of SBR or synthetic rubber workers.

4.3.1. McMichael et al. (1974, 1976)

In 1974, McMichael et al. identified, through company records, a historic

prospective cohort of 6,678 hourly paid male workers in a rubber tire manufacturing plant in Akron, Ohio. The cohort was composed of all active and retired male employees aged 40 to 84 years as of January 1, 1964.

During the 9-year follow-up period from 1964 through 1972, 1,783 workers died. Death certificates were obtained for 99.5% of these workers, and the causes of death were coded according to the 8th revision of the International Classification of Diseases (ICD), by a National Center for Health Statistics nosologist.

SMRs were calculated for all males using the 1968 U.S. male population as a standard population. SMRs for all causes for the active age range of 40-64 and the full age range of 40-84 were 93 and 99, respectively. In cause-specific SMRs, statistically significant excesses were observed for stomach cancer (SMR = 219, observed = 12, expected = 5.5, $p < 0.01$), lymphosarcoma (SMR = 251, observed = 6, expected = 2.4, $p < 0.05$), and leukemia (SMR = 315, observed = 11, expected = 3.5, $p < 0.001$), in the active age range of 40-64. For the full age range of 40-84, significant SMR increases were observed for cancers of the stomach (SMR = 187, observed = 39, expected = 20.9, $p < 0.001$), prostate, (SMR = 142, observed = 49, expected = 34.4, $p < 0.05$), lymphosarcoma (SMR = 226, observed = 14, expected = 6.2, $p < 0.01$), diabetes mellitus (SMR = 143, observed = 43, expected = 30, $p < 0.05$), and arteriosclerosis (SMR = 154, observed = 34, expected = 22.1, $p < 0.05$).

McMichael et al. (1976) attempted to evaluate the relationship of these mortality excesses to specific jobs within this plant by designing a nested case-control study. Out of a total of 1,983 deaths observed during the 10-year follow-up period of 1964 through 1973, 455 individuals who had died from certain specific causes were selected as cases. The specific causes of death included stomach, colorectal, respiratory, prostate, and bladder cancers; cancers of the

lymphatic and hematopoietic systems; lymphatic leukemias; ischemic heart disease; and diabetes mellitus. Out of these 455 cases, 353 deaths were attributed to cancers and 102 to noncancer causes. From the remainder of the plant population of male workers, an age-stratified random sample of 1,500 individuals, with 500 individuals in each age group of 40-54, 55-64 and 65-84 was obtained. Complete work histories were obtained for 99% (1,482) of this age-stratified sample drawn as a control group.

As of January 1, 1964, the plant population of male workers had a racial composition of 86% white and 14% black. Thirty-eight percent, 30%, and 32% were in the 40-54, 55-64, and 65-84 age ranges, respectively. Forty-eight percent had begun work in the plant at least 25 years prior to 1964, and 99% had worked for at least 10 years by 1964.

Work exposure histories were restricted to the period from 1940 through 1960. Cumulative job exposures of less than 2 years were excluded from the analyses. Because follow-up extended to 1972, the period between first exposure and death could range from 12 to 32 years, which should allow for the observation of occupationally induced cancers in adults.

For each of the cause-specific mortality groups, as well as the group of controls, rates of exposure for minimum duration of 2 years and 5 years were calculated for each of 16 occupational title groups (OTGs) in order to ascertain any dose-response relationships. The exposure rates in each case group were age-adjusted by the direct method of adjustment to the age distribution of the controls. For the nine cause-specific mortality groups, the ratios of their age-adjusted job classification exposure rates to the rates within the sample of controls were calculated in order to provide an approximation for the more conventional odds ratios.

For all of the causes of death under investigation, there were statisti-

cally significant ($p < 0.001$) associations with many of the work areas in which workers had had at least 5 years of exposure. In the synthetic plant area, the significant ($p < 0.001$) risk ratios were 6.2 for lymphatic and hematopoietic cancer, 3.9 for lymphatic leukemia, 3.0 for ischemic heart disease, and 2.2 for stomach cancer. Among the various work areas, the risk ratios for lymphatic leukemia and for lymphatic and hematopoietic cancer were the highest in the synthetic plant. Spirtas (1976) reported, however, that the risk ratio for lymphatic and hematopoietic cancer dropped from 6.2 to 2.4 when a smaller matched control group was used; the statistical significance of the 2.4 risk ratio was not indicated.

McMichael et al. (1976) reported that a case-control study (McMichael et al., 1975) had found an association between lymphatic leukemia and solvent exposure in the rubber industry. Many of the lymphatic leukemia deaths were the same as those reported in the McMichael et al. (1976) study. Further analysis by Checkoway et al. (1984) of 11 of the lymphatic leukemia cases studied by McMichael et al. also found an association between lymphatic leukemia and solvent exposure. Spirtas (1976) reported that of the six deaths from neoplasms of lymphatic and hematopoietic tissue of individuals who had worked in the synthetic rubber area of the plant in the McMichael et al. (1976) study, three were due to leukemia. Of these three individuals, two had had experience with solvents other than in the synthetic plant. Thus the role of the transfer of individuals from one work area into another needs to be investigated. Also, racial factors could not be accounted for in exposure calculations because data on race were not available for much of the study population at the time of sampling.

4.3.2. Andjelkovich et al. (1976, 1977)

The mortality experience during the period from January 1, 1964 through December 31, 1973 of a historic prospective cohort of 8,938 male rubber workers

(known as the "1964 cohort") from a single plant located in Akron, Ohio, was observed by Andjelkovich et al. in 1976. Any person who was 40 years of age or more on January 1, 1964, and was an active or living retired hourly worker from the plant under study, was included in the 1964 cohort.

Data were collected from company records, life insurance death claims, and bureaus of vital statistics of several states. A trained nosologist coded the causes of death according to the 8th revision of the ICD. Follow-up was achieved for 96.7% of the cohort. Out of 8,938 males, 94% (8,418) were white males and were equally distributed in the age groups 40-54, 55-64, and 65-84. Although 6% of the cohort consisted of black males, the major analyses were done on white males. During the 10-year observation period 2,373 (28%) of the white males died. SMRs were calculated using the age-, race-, and sex-specific rates of the 1968 U.S. population. SMRs for deaths from all causes in the 40-64, 65-84, and 40-84 age groups were, respectively, 92 (observed = 619), 95 (observed = 1,754, $p < 0.05$) and 94, (observed = 2,373, $p < 0.01$).

Many cause-specific SMRs showed increases, but only two disease SMRs, those for neoplasms of lymphatic and hematopoietic tissue (SMR = 138, observed = 40) and chronic rheumatic heart disease (SMR = 170, observed = 16) for the age group 65-84 were statistically significant ($p < 0.05$). The only statistically significant ($p < 0.05$) SMR for the age group 40-64 was for cerebrovascular disease (SMR = 138, observed = 48). On further detailed examination of neoplasms of lymphatic and hematopoietic tissue, statistically significant excesses were found for monocytic leukemia (SMR = 441, observed = 3, $p < 0.01$) and other neoplasms of lymphatic and hematopoietic tissue (SMR = 276, observed = 10, $p < 0.001$) in the age group 65-84. There were no deaths by either of these causes in the age group 40-64.

An important finding of this study is that it found a high mortality rate

in workers who had retired between the ages of 40 and 64, the mandatory retirement age being 65. The SMR for all causes for this group was 202, which is highly statistically significant (observed = 299, $p < 0.001$). The SMR for almost every cause analyzed was elevated, and out of 26 categories, 13 of them were statistically significant. For malignant diseases, the authors found significant elevations in SMRs for malignant neoplasms of the prostate (SMR = 278, observed = 4, $p < 0.05$); large intestine (SMR = 231, observed = 6, $p < 0.05$); trachea, bronchus, and lung (SMR = 241, observed = 28, $p < 0.001$); and brain and central nervous system (SMR = 323, observed = 3, $p < 0.05$). In non-malignant diseases, SMRs were statistically significant for 1) benign neoplasms and neoplasms of unspecified nature (SMR = 541, observed = 2, $p < 0.01$); 2) endocrine, nutritional, and metabolic diseases (SMR = 396, observed = 11, $p < 0.001$); 3) diseases of the nervous system and sense organs (SMR = 577, observed = 6, $p < 0.001$); 4) chronic rheumatic heart disease (SMR = 440, observed = 7, $p < 0.001$); 5) ischemic heart disease (SMR = 180, observed = 112, $p < 0.001$); 6) cerebrovascular disease (SMR = 258, observed = 22, $p < 0.001$); 7) other respiratory disease (SMR = 309, observed = 5, $p < 0.01$); 8) diseases of the digestive system (SMR = 357, observed = 16, $p < 0.01$); and 9) symptoms and ill-defined conditions (SMR = 263, observed = 4, $p < 0.05$).

As opposed to these increases, the SMR for deaths from all causes for active workers in the 40-64 age group was 61 (observed = 320), substantially lower than the SMR of 202 for retired workers in this age group. The overall SMR for active and retired workers combined was 92 (observed = 619), showing a dilution effect by the active workers and confirming the "healthy worker" effect. Some cause-specific SMRs were elevated slightly in this active group, but none of them were statistically significant.

In an attempt to evaluate the relationship between the mortality increases

and occupational exposures, Andjelkovich et al. (1977) re-analyzed the same data for 28 work areas within the plant under study in 1977. The Occupational Title Group (OTG) of each person was decided on the basis of the most representative department (obtained from personnel folders) in which the individual had worked. The closing date for the active workers was December 31, 1973, while for the retired or terminated workers the period of study was from the date of hire to the last date worked.

All causes of death and cause-specific SMRs were calculated by using the experience of the entire cohort as a reference group. Marginal increases in SMRs for all causes were observed for many OTGs for all three of the age groups considered: 40-64, 65-84, and 40-84 years. The only statistically significant excess observed was for cast film manufacture (SMR = 230, observed = 7, $p < 0.05$) in age group 65-84. Statistically significant ($p < 0.05$) SMR deficits from all causes were observed for OTGs: 1) product fabrication (tire and beads), 2) product fabrication (valves, tubes, and flaps), and 3) bulk chemicals and metal products, for at least one or more of the three age groups.

SMR increases were statistically significant for all neoplasms in the following four OTGs: 1) cast film manufacture for age group 40-84, 2) special products manufacture for age group 40-84, 3) milling for age groups 65-84 and 40-84, and 4) miscellaneous for age groups 40-64 and 40-84. Out of these four OTGs, the first three departments dealt with the manufacture of industrial products.

For selected cancers, the SMRs were significantly ($p < 0.05$) elevated in age group 40-84 in certain OTGs, namely, cancer of the stomach in compounding and mixing (SMR = 479, observed = 3), and milling (SMR = 369, observed = 6); cancer of the large intestine in special products (SMR = 629, observed = 4); cancers of the trachea, bronchus, and lung in synthetic latex (SMR = 434,

observed = 3); cancer of the prostate (SMR = 212, observed = 10); and leukemia (SMR = 246, observed = 6) in general services. All SMRs, except the one for the compounding and mixing department, showed statistically significant excesses of deaths in more than one age group.

For non-malignant diseases, Andjelkovich et al. (1977) calculated significantly ($p < 0.05$) elevated SMRs for diabetes mellitus, acute myocardial infarction, arteriosclerosis, and suicide in various OTGs for various age groups. Significant excesses of deaths in the general service department and arteriosclerosis in the shipping and receiving department were observed in more than one age group. Statistically significant deficits were observed for ischemic heart disease in the industrial chemicals department and acute myocardial infarction in the stock preparation department, both in the 40-84 age group.

Since the authors were aware that the job transfer patterns of the deceased workers were not necessarily representative of the job transfer patterns of the entire cohort, they used the available information on deceased workers to estimate the length of time spent in the most representative department. A simple random sample of 50 deceased workers was chosen, and detailed work histories were reviewed for them. The 50 workers had spent an average of 28.3 years in the industry. On an average, each worker had spent 50% of his work time in his most representative OTG. However, the fraction of time spent in the most representative OTG ranged from less than 10% up to 100% of total employment duration.

The Andjelkovich et al. studies have a number of limitations. First, their use of the most representative departments should be questioned in view of the fact that the people under study could have worked in these departments from 10% to 100% of their total employment duration. The only elevated SMR in synthetic latex was for cancer of the trachea, bronchus, and lung, based on only

three deaths, while cigarette smoking, which is a potential confounder, was not controlled for. Another limitation with regard to the observed elevation of trachea, bronchus, and lung cancer was the use of 1968 mortality data to calculate the expected number of deaths. Mortality for trachea, bronchus, and lung cancer was rising sharply during the period 1964 to 1983, the follow-up period of this study. The use of 1968 data may have underestimated the expected number of deaths and thus overestimated the SMR. Although a statistically significant excess of deaths for cancers of lymphatic and hematopoietic tissue was observed for persons whose most representative department was general services, this job category does not necessarily involve contact with SBR production. With regard to the questionable exposure, Taulbee et al. (1976) reported that in an analysis of the work histories of 37 leukemia cases and four matched controls per case from the 1964 cohort of Andjelkovich et al., none of the cases were found to have worked in the OTG "synthetic plant." Some of the cases had worked in departments in which there may have been exposure to the synthetic process, but this association was not statistically significant ($p < 0.05$), nor was the association found to increase by duration of exposure.

One positive aspect of the Andjelkovich et al. (1977) study is that the entire cohort is used as a reference group, which should reduce the "healthy worker effect" and allow for a more unbiased evaluation. It would have been interesting, however, to see the comparison of SMRs calculated from the U.S. population (1968), which was used as a standard population in the 1976 study, with the SMRs calculated from the internal cohort as a reference group.

Both the McMichael et al. and the Andjelkovich et al. studies are suggestive of some health problems in the synthetic plant, indicating that specific exposure investigations should be undertaken.

4.3.3. Checkoway and Williams (1982)

Since the study of McMichael et al. (1976) indicated the potential presence of carcinogens in SBR plants, Checkoway and Williams conducted a combined industrial hygiene and hematology cross-sectional survey at the same plant studied by McMichael et al. The objectives of the Checkoway and Williams study were to quantify workplace exposures to styrene, butadiene, benzene, and toluene, and to relate exposure levels to hematologic measurements.

During the week of May 15-19, 1979, personal breathing-zone air samples were collected with both a charcoal tube and a passive diffusion dosimeter during the day and evening shifts for seven different departments. The departments were: 1) tank farm, 2) reactor and recovery, 3) latex blending and solution, 4) shipping and receiving, 5) storeroom, 6) factory service, and 7) maintenance areas. Sampling periods ranged from 4 to 6 hours. Charcoal tubes were changed at intervals of 1 to 2 hours during the sampling period to avoid overloading.

Blood samples of male hourly production workers for the same departments were obtained on 4 separate days, May 15-18. Of the 163 workers (26-65 years of age with a median age of 45 years; 144 whites and 19 blacks) who participated in the industrial hygiene survey, 154 (135 whites and 19 blacks) also participated in the blood survey. Because of work scheduling demands, blood samples were collected from participants from each of the departments on all 4 days, thereby minimizing any bias due to day effect. The hematological parameters measured included red cell count (RBC), hemoglobin concentration, hematocrit, mean corpuscular volume (MCV), mean corpuscular hemoglobin concentration, reticulocyte count, platelets, total leukocytes (WBC), and differential distributions of neutrophils, neutrophil band forms, eosinophils, basophils, monocytes, and lymphocytes. Medical histories were obtained by means of questionnaires.

Data from persons who reported positive histories of either malignant disease, radiation therapy, or current anemia of known etiology were excluded from the analyses. Only one individual, who reported a history of leukemia, was excluded from the study.

The mean 8-hour time-weighted averages and ranges show that all four chemical exposures were well below the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) recommended at that time. The TLVs in parts per million (ppm) for butadiene, styrene, benzene, and toluene are 1,000, 100, 10, and 100, respectively. With the exception of butadiene and styrene, for which time-weighted averages of 20.03 ppm and 13.67 ppm, respectively, were observed in the tank farm area, the mean levels for the four chemicals in all other departments were less than 2 ppm. Even the maximum concentration of benzene, the most strongly suspected leukemogen of the four chemicals analyzed, was less than 1 ppm in all plant departments.

With regard to the hematologic survey, there were generally no associations ($p > 0.05$) of hematologic values with chemical exposures. Red blood cell count was negatively associated with butadiene and styrene exposure, while basophil count was positively related to the aforementioned chemicals, as measured by Pearson product moment analysis. The negative association of styrene with erythrocyte counts and the positive association of the basophil proportions with butadiene persisted after controlling for age and medical status in stepwise multiple linear regression analyses. However, there were curious opposing findings for mean corpuscular hemoglobin concentration--a positive relationship to butadiene and a negative association with styrene.

Mean hematologic mesurements adjusted for age and medical status were compared for tank farm area workers and all other workers. The tank farm workers had slightly lower levels of circulating erythrocytes, hemoglobin, platelets,

and neutrophils, in addition to mean corpuscular red cell volumes and neutrophil band circuits that were slightly higher than those of the other workers.

This study was undertaken to quantify exposure levels and to find out if there is any evidence of hematopoietic toxicity in relation to these exposure levels. With the exception of the tank farm area, the average exposures to the four chemicals assayed were uniformly less than 2 ppm; even in the tank farm area, the styrene and butadiene concentrations were considerably lower than the recommended ACGIH TLVs, although they were considerably higher than in other work places studied.

Because this study is cross-sectional in design, it is very limited with regard to determining whether styrene-butadiene exposure is carcinogenic. Individuals in the plant who may have developed cancer probably left the work force and hence were not available for blood sampling. The industrial hygiene survey findings cannot be generalized to the past, since the concentrations may have differed quantitatively as well as qualitatively. It can be concluded that there was no pronounced evidence of hematologic abnormality in this study population.

4.3.4. Meinhardt et al. (1982)

Meinhardt et al. (1982) reported on a retrospective cohort mortality study conducted by NIOSH at two adjacent SBR facilities in eastern Texas. This study was motivated by the report of two men who had worked at both plants, and who had died of leukemia in January 1976.

Personnel employment records documenting the employment of 3,494 workers from plant A and 2,015 from plant B were available since January 1943 and January 1950, respectively, to the study cut-off date of March 31, 1976. The study cohorts from plants A and B consisted of 1,662 and 1,094 white males who had had at least 6 months of non-management and non-administrative employment,

respectively. The average lengths of employment for the study cohort in plants A and B were, respectively, 9.48 and 10.78 years.

At the time of the study, environmental samples were obtained at each plant. At plant A, time-weighted average exposures of styrene, butadiene, and benzene were 0.94 ppm (0.03-6.46), 1.24 ppm (0.11-4.17) and 0.10 ppm (0.08-0.14) respectively. For plant B, time-weighted average exposures for styrene and butadiene were 1.99 ppm (0.05-12.3) and 13.5 ppm (0.34-174.0), respectively (benzene was not measured). No historical monitoring data were available for either plant.

The study cohorts from plants A and B accounted for 34,187 and 19,742 person-years at risk of dying. It is also important to note that the survival status of 54 individuals (3.25%) from cohort A and 34 individuals (3.11%) from cohort B was unable to be determined. In subsequent analyses, these individuals were considered to be alive.

The age, race, sex, calendar time, and cause-specific mortality rates of the U.S. population were applied to the appropriate strata of person-years at risk in order to obtain the expected number of cause-specific deaths in the study populations. Differences in observed and expected numbers of deaths were evaluated by a test statistic based on the Poisson distribution.

In cohorts from plants A and B, observed and expected numbers of deaths were compared for the following cause-specific categories: tuberculosis; malignant neoplams (including cancers of the lymphatic and hematopoietic tissues); all other cancers; diseases of the nervous, circulatory, respiratory, and digestive systems; accidents; and all other causes. With the exception of mortalities from cancers of the lymphatic and hematopoietic tissues, there were deficits (in some instances, striking deficits) in the cause-specific SMRs for the study cohorts in both the plants.

With regard to the total number of deaths due to all causes, cohorts A and B had observed numbers of deaths of 252 (SMR = 80) and 80 (SMR = 66), respectively. Although it is possible that the "healthy worker" effect may, in part, explain these deficits, the relative magnitudes of the deficits, particularly for plant B, suggest that there may have been an underreporting of deaths or that selection factors in the choice of the study groups reduced the mortality rate.

Meinhardt et al. observed that all five of the individuals from plant A whose underlying cause of death was leukemia began employment before the end of December 1945. This date corresponds to the time when the batch process for SBR production was converted to a continuous-feed operation. The decision was made, therefore, to evaluate the mortality experience of those 600 white male employees who had had at least 6 months of employment in plant A between January 1, 1943 and December 31, 1945. This subgroup was employed for an average of 11.9 years, and had an accumulation of 17,086 person-years at risk of dying. The survival status of 34 individuals (5.7%) was unknown. As in the previous mortality analyses, with the exception of deaths from cancers of the lymphatic and hematopoietic tissues, there generally were large deficits in the cause-specific observed number of deaths. For malignant neoplasms of lymphatic and hematopoietic tissues, the SMR was 212 (9 observed, 4.25 expected, $0.05 < p < 0.1$); for lymphosarcoma and reticulosarcoma the SMR was 224 (3 cases, 1.34 expected, $p > 0.05$); for Hodgkin's disease the SMR was 213 (1 case, 0.47 expected, $p > 0.05$); and for leukemia and aleukemia the SMR was 278 (5 cases, 1.80 expected, $0.05 < p < 0.1$). The total number of observed deaths due to all causes was 201 (SMR = 83, 242.09 expected, $p < 0.05$). For cohort B, there were no significant ($p > 0.05$) excesses of mortality from any cause. Deaths from all malignant neoplasms (SMR = 53, observed = 11, expected = 20.78, $p < 0.05$) and "all other causes" (SMR = 54, observed = 9, expected = 16.80, $p <$

0.05) were significantly decreased, however.

The authors calculated the likelihood of detecting a doubling and a quadrupling of the expected occurrence of leukemia for cohort A, subcohort A, and cohort B. These likelihoods were 26% and 88% for cohort A, 20% and 77% for subcohort A, and 13% and 51% for cohort B. Thus, this study suggests that some component of the SBR manufacturing process may be a leukemogen.

4.3.5. Matanoski et al. (1982)

This study was performed to determine whether there are health risks associated with the production of synthetic rubber, specifically styrene-butadiene rubber (SBR). The populations studied were obtained from seven U.S. and one Canadian rubber plants. The study population consisted of males who had worked for more than one year, and whose records contained birth dates and employment dates. In addition, workers selected had been employed by the facility from the date of the facility's first SBR production to December 1976. The total number of people available from the eight plants surveyed was 29,179, of whom 13,920 (48%) met the criteria for selection.

Data obtained from the personnel records of each facility included employee name, Social Security number, job history, date(s) of employment, birth information, death information, and limited data on retirees. Individual workers' jobs were coded according to first job, last job, and job held longest during the period of employment. For the analyses, jobs were categorized in four general work areas: production, utilities, maintenance, and other. In three plants (plants 3, 4, and 5), race classification was unknown for 176 (85%), 329 (50%), and 4,540 (98%) of the cohort populations, respectively. Plants 3 and 4 were expected to have employed black workers; plant 5 had employed few or no blacks at any time in its history. In all, 7,209 (52%) of the study population were unable to be classified racially. If race was not specified, indivi-

duals were assumed to be white males.

Follow-up activities to determine vital status of the study population in the seven U.S. plants included searching by the Social Security Administration, tracing through motor vehicle administration records, and contacts by telephone. Through these follow-up activities, 42% of the study population were traced. For the Canadian plant, follow-up was performed by searching the company insurance plan records for death benefit information. Determination of vital status for the study populations revealed 10,899 workers alive, 2,097 known dead, and 924 lost to follow-up. It was determined from a 10% sample in each plant that about 4% of the study population assumed to be living was actually dead. Thus, as many as 440 deaths, or 17% of the total possible deaths, might have been missed. For the populations who were known dead, 90% of the death certificates requested were received. Death certificates were coded according to the 8th revision of the ICD.

Most of the statistical analyses were done using the worker records from the time when record-keeping systems became complete, or any time thereafter through December 1976. Females, workers employed less than one year, and those with unknown birth dates or employment dates were omitted. The total eligible population numbered 13,608. SMRs for the workers as compared to the general population were calculated by using a modified version of U.S. Death Rates Programs (Monson, 1979). SMRs were calculated separately for the white population and the black population, and the ratios were combined to correct for differences in age, race, and calendar time. The total number of deaths occurring among the eligible study population was 1,995, with an SMR of 81. The study cohort accounted for 250,000 person-years.

Power calculations were performed to test the ability of the data to determine increases in risk of 0.1, 0.25, 0.5, and 2 times greater then the U.S.

population. The calculations showed a 100% probability of detecting a twofold increase in all causes of death and in all cancers, and an 89% probability of detecting a 25% increase in lung cancer.

The average period of follow-up was 19 to 20 years. The average age at death was 61 years. The overall SMR for all causes of death was 81, with SMRs of 98 for blacks and 78 for whites. The low mortality among members of this population is, in part, a reflection of the "healthy worker" effect. However, a question must also be raised as to the effect of the 440 possible deaths that may have been missed. Furthermore, the large difference in SMRs for blacks and whites may be due to an undercounting of blacks and an overcounting of whites. This is further exemplified by similar patterns in SMRs for all accidents, motor vehicle accidents, and suicides. The SMRs for all causes of death do not appear to increase with duration of employment but do appear to increase with increasing follow-up period.

The leukemias found in the population included nine acute, five chronic, and three unspecified on the death certificate, with a median latent period of 17 years from time of first employment. The types found were not considered to have a distribution remarkably different from that found in the general population. The study population as a whole did not demonstrate leukemia in excess.

None of the analyses demonstrated significant increases in SMRs for other specific causes in the total study population. Black males appear to have a significantly elevated risk of arteriosclerotic heart disease ($p < 0.05$), but this value may be artificially inflated due to undercounting of the blacks, resulting in a smaller denominator. Vascular lesions of the central nervous system were also in excess in black males, but they were not statistically significant.

Increases in mortality according to job classifications are noteworthy, but only two of them are statistically significant ($p < 0.05$). The SMR for testicular cancer among maintenance workers is 294 (observed = 3, $p < 0.05$). SMRs for esophagus, stomach and large intestine, and larynx cancers are elevated in the utilities and maintenance work areas. The SMR for larynx cancer in utilities workers is statistically significant (SMR = 476, observed = 4, $p < 0.05$). Hodgkin's disease is associated with high SMRs in all work areas. Very few high SMRs are found for the production area.

It should be further pointed out that, with the exceptions of Hodgkin's disease and stomach cancer, all of the cancers had relatively long latent periods. For all cancers, half of the individuals had had 12 years of employment or more.

In addition to complete ascertainment of deaths and racial distribution, further investigation is needed in order to obtain information specific to various jobs and the associated exposures of individuals in those jobs. It would also be useful to separate the number of years employed within each job category, in order to determine the periods of possible exposure in the workplace. Moreover, changes in the SBR process, in plant design, and in worker practices should be given greater attention in the evaluation of mortality for the four worker categories studied.

Other methodologic limitations of this study include the fact that less than 50% of the total population of eight plants was studied. This raises questions about the population that was excluded due to lack of birth dates or employment dates. This may have been an older population, which probably had longer exposure and was therefore more likely to suffer from occupational diseases. Out of eight cohorts, only 50% were followed from 1943, whereas in the rest of the plants, follow-up starting dates ranged from 1953 to 1970. It

is probable that the employees from the latter plants were not followed long enough for malignancies to develop.

4.3.6. Summary of Epidemiologic Studies

McMichael et al. (1974) found significant ($p < 0.05$) excess mortality from cancers of the stomach, prostate, and lymphatic and hematopoietic system as well as from diabetes mellitus, arteriosclerosis, and ischemic heart disease in their historic prospective cohort study. To evaluate these excesses, McMichael et al. (1976), in a case-control study, investigated exposure rates for various jobs within the same rubber plant for several cause-specific deaths. The data indicated that the most probable health risks were of prostate cancer in janitoring and trucking; bladder cancer in milling and reclaiming operations; lymphatic and hematopoietic cancers in the synthetic plant; and lymphatic leukemia in the synthetic plant, inspection-finishing-repair, and tread cementing. Nonmalignant mortality excesses included ischemic heart disease in the synthetic plant and tread cementing and diabetes mellitus in janitoring and trucking and inspection-finishing-repair.

Andjelkovich et al. (1976) carried out a similar kind of study (historic prospective cohort) in white males in a single rubber plant, and observed significantly ($p < 0.05$) increased SMRs for malignant neoplasms of lymphatic and hematopoietic tissues (monocytic leukemia and other neoplasms of lymphatic and hematopoietic tissue), chronic rheumatic heart disease, and cerebrovascular disease. They also observed high SMRs ($p < 0.001$) for all causes and for most of the cause-specific deaths for a group of workers who had retired between the ages of 40 and 64. Andjelkovich et al. (1977) evaluated these excesses in mortality ratios in relation to various work areas by using the entire cohort as a reference group, and found that only malignant neoplasms of the trachea, bronchus, and lung were associated with the synthetic latex department. This

finding was based on only three observed deaths, however, and no smoking data were taken.

Checkoway and Williams (1982) carried out an industrial hygiene and hematology cross-sectional survey at the same plant in which McMichael et al. had conducted their case-control study. With the exception of the tank farm area, in which 8-hour time-weighted averages for butadiene and styrene were observed to be 20.3 ppm and 13.67 ppm, respectively, all other departments had mean exposure levels of less than 2.0 ppm. No evidence of hematologic abnormality was noted. Because of its cross-sectional design, however, this study could not be expected to identify an excess cancer risk.

Meinhardt et al. (1982), conducted a retrospective cohort mortality study at two plants in Texas. Male rubber workers in one of the plants (plant A) were followed from January 1, 1943 through March 31, 1975; employees in the other plant (plant B) were followed from January 1, 1950 through March 31, 1976. These intervals of observation are important to note because the two plants changed from a batch process for SBR production to a continuous-feed operation in 1946. With regard to cancers of the lymphatic and hematopoietic system and lymphatic leukemia, plant A exhibited excess mortalities, although these were not statistically significant ($p > 0.05$); plant B did not show any mortality excesses. When the mortality experience in plant A was analyzed further for those workers who had had at least 6 months of employment between January 1, 1943, and December 31, 1945 (the interval for which the batch process was used), excess mortalities for the above-mentioned cancers were shown to be of borderline statistical significance ($0.05 < p < 0.01$, two-sided). It is also of interest to note that all of the employees from the total cohort of plant A whose causes of death were cancers of the lymphatic and hematopoietic tissues had been employed between 1943 and 1945. Had the analysis in plant A

commenced with the date of first employment in 1946, the SMRs in question would have been reduced to zero, and the lack of excess mortality would have been similar to plant B.

Matanoski et al. (1982) also conducted a retrospective cohort mortality study in which eight SBR plants were involved. As with the cohort in plant B investigated by Meinhardt et al., there was a general lack of excess mortalities. It should also be noted that half of the cohort was followed from 1943 to 1979. The date of entry for the remaining half of the cohort ranged from 1953 to 1976, with follow-up terminating in 1979.

Although both the McMichael et al. (1976) and the Meinhardt et al. (1982) studies found some evidence of an association between styrene-butadiene exposure and lymphatic and hematopoietic cancer, confounding due to exposures to solvents cannot be ruled out for either study. In addition, the results from the Meinhardt et al. study for the subcohort employed during the batch process of production were only of borderline ($0.05 < p < 0.1$, two-sided) significance, and a possibly serious underascertainment of deaths, and/or selection factors in the choice of the study group may have biased the results.

The Andjelkovich et al. (1977) study found an association between employment in the synthetic part of the plant with mortality from cancer of the trachea, bronchus, and lung. The association was based on only three deaths, however, and there was no control for smoking.

The study by Matanoski et al. of almost 14,000 styrene-butadiene production workers found no excesses of cancer mortality that were statistically significant ($p < 0.05$). Again, however, a possibly serious underascertainment of deaths may have biased the results. An undercounting of blacks in the study population may also have resulted in a potential bias.

The epidemiologic evaluation of SBR workers with regard to the carcinoge-

nicity of 1,3-butadiene is particularly difficult because styrene may also be a carcinogen and, in particular, a leukemogen (Ott et al., 1980; Lilis and Nicholson, 1976). Because of the inconsistency of the results from different studies, the possible confounding due to solvent and styrene exposures, and the potential for bias in some of the studies, the epidemiologic data are considered inadequate for determining a causal association between 1,3-butadiene exposure and cancer in humans.

4.4. QUANTITATIVE ESTIMATION

This section deals with the incremental unit risk for 1,3-butadiene in air, and the potency of 1,3-butadiene relative to other carcinogens that the CAG has evaluated. The incremental unit risk estimate for an air pollutant is defined as the excess lifetime cancer risk occurring in a hypothetical population in which all individuals are exposed continuously from birth throughout their lifetimes to a concentration of 1 g/m^3 of the agent in the air they breathe. This calculation estimates in quantitative terms the impact of the agent as a carcinogen. Unit risk estimates are used for two purposes: 1) to compare the carcinogenic potency of several agents with each other, and 2) to give a crude indication of the population risk that might be associated with air exposure to these agents if the actual exposures were known. Hereafter, the term "unit risk" will refer to incremental unit risk.

4.4.1. Procedures for Determination of Unit Risk

The data used for quantitative estimation ar_ taken from one or both of the following: 1) lifetime animal studies, and 2) human studies where excess cancer risk has been associated with exposure to the agent. In animal studies it is assumed, unless evidence exists to the contrary, that if a carcinogenic response occurs at the dose levels used in the study, then responses will also occur at all lower doses, with an incidence determined by an extrapolation model.

There is no solid scientific basis for any mathematical extrapolation model that relates carcinogen exposure to cancer risks at the extremely low concentrations that must be dealt with in evaluating environmental hazards. For practical reasons, such low levels of risk cannot be measured directly either by animal experiments or by epidemiologic studies. We must, therefore, depend on our current understanding of the mechanisms of carcinogenesis for guidance as to which risk model to use. At the present time the dominant view of the carcinogenic process involves the concept that most agents that cause cancer also cause irreversible damage to DNA. This position is reflected by the fact that a very large proportion of agents that cause cancer are also mutagenic.

There is reason to expect that the quantal type of biological response, which is characteristic of mutagenesis, is associated with a linear nonthreshold dose-response relationship. Indeed, there is substantial evidence from mutagenicity studies with both ionizing radiation and a wide variety of chemicals that this type of dose-response model is the appropriate one to use. This is particularly true at the lower end of the dose-response curve; at higher doses, there can be an upward curvature, probably reflecting the effects of multistage processes on the mutagenic response. This linear nonthreshold dose-response relationship is also consistent with the relatively few epidemiologic studies of cancer responses to specific agents that contain enough information to make the evaluation possible (e.g., radiation-induced leukemia, breast and thyroid cancer, skin cancer induced by arsenic in drinking water, liver cancer induced by aflatoxin in the diet). There is also some evidence from animal experiments that is consistent with the linear non-threshold model (e.g., liver tumors induced in mice by 2-acetylaminofluorene in the large-scale ED_{01} study at the National Center for Toxicological Research, and the initiation stage of the

two-staye carcinogenesis model in rat liver and mouse skin).

Based on the above evidence of low-dose linearity, and because very few compounds exhibit low-dose responses that are superlinear, the linear non-threshold model has been adopted as the primary basis for risk extrapolation to low levels of the dose-response relationship. The incremental risk estimates made with this model and the corresponding 95% upper-limit incremental unit risks, should be regarded as conservative, representing the most plausible upper limits for the risk, i.e., the true risk is not likely to be higher than the estimates, but it could be lower.

The mathematical formulation chosen to describe the linear nonthreshold dose-response relationship at low doses is the linearized multistaye model. This model employs enough arbitrary constants to fit almost any monotonically increasing dose-response data, and it incorporates a procedure for estimating the largest possible linear slope (in the 95% confidence limit sense) at low extrapolated doses that is consistent with the data at all dose levels of the experiment. The multistage model, described below, is fit to the data in the observational or experimental range. The fit of the curve allows for a linear term which dominates the risk estimate at low doses. The 95% upper limit, described below, is technically an upper-limit estimate on the linear term, but, practically, functions as the upper-limit low dose-response function.

4.4.1.1. Description of the Low-Dose Extrapolation Model

Let P(d) represent the lifetime risk (probability) of cancer at dose d. The multistage model has the form

$$P(d) = 1 - \exp\left[-(q_0 + q_1 d + q_1 d^2 + \ldots + q_k d^k)\right]$$

where

$$q_i \geq 0, \; i = 0, 1, 2, \ldots, k$$

Equivalently,

$$P_t(d) = 1 - \exp\left[-(q_1 d + q_2 d^2 + \ldots + q_k d^k)\right]$$

where

$$P_t(d) = \frac{P(d) - P(0)}{1 - P(0)}$$

is the extra risk over background rate at dose d.

The point estimate of the coefficients q_i, i = 0, 1, 2, ..., k, and consequently, the extra risk function, $P_t(d)$, at any given dose d, is calculated by maximizing the likelihood function of the data.

The point estimate and the 95% upper confidence limit of the extra risk, $P_t(d)$, are calculated by using the computer program GLOBAL83, originally developed by Crump and Watson (1979). At low doses, upper 95% confidence limits on the extra risk and lower 95% confidence limits on the dose producing a given risk are determined from a 95% upper confidence limit, q_1^*, on parameter q_1. Whenever $q_1 > 0$, at low doses the extra risk $P_t(d)$ has approximately the form $P_t(d) = q_1 \times d$. Therefore, $q_1^* \times d$ is a 95% upper confidence limit on the extra risk, and R/q_1^* is a 95% lower confidence limit on the dose, producing an extra risk of R. Let L_0 be the maximum value of the log-likelihood function. The upper-limit, q_1^*, is calculated by increasing q_1 to a value q_1^* such that when the log-likelihood is remaximized subject to this fixed value q_1^* for the linear coefficient, the resulting maximum value of the

log-likelihood L_1 satisfies the equation

$$2\ (L_0 - L_1) = 2.70554$$

where 2.70554 is the cumulative 90% point of the chi-square distribution with one degree of freedom, which corresponds to a 95% upper limit (one-sided). This approach of computing the upper confidence limit for the extra risk $P_t(d)$ is an improvement on the Crump et al. (1977) model. The upper confidence limit for the extra risk calculated at low doses is always linear. This is conceptually consistent with the linear nonthreshold concept discussed earlier. The slope, q_1^*, is taken as an upper bound of the potency of the chemical in inducing cancer at low doses.

In fitting the dose-response model, the number of terms in the polynomial is chosen equal to (h-1), where h is the number of dose groups in the experiment, including the control group.

Whenever the multistage model does not fit the data sufficiently well, data at the highest dose is deleted and the model is refit to the rest of the data. This is continued until an acceptable fit to the data is obtained. To determine whether or not a fit is acceptable, the chi-square statistic

$$\chi^2 = \sum_{i=1}^{h} \frac{(X_i - N_i P_i)^2}{N_i P_i\ (1-P_i)}$$

is calculated where N_i is the number of animals in the i^{th} dose group, X_i is the number of animals in the i^{th} dose group with a tumor response, P_i is the probability of a response in the i^{th} dose group estimated by fitting the

multistage model to the data, and h is the number of remaining groups. The fit is determined to be unacceptable whenever X^2 is larger than the cumulative 99% point of the chi-square distribution with f degrees of freedom, where f equals the number of dose groups minus the number of non-zero multistage coefficients.

When all the higher order terms in the multistage model are zero except the linear term, the multistage model reduces to the one-hit model, which is a true low-dose linear nonthreshold model. As will be seen with the animal data, this is the case with 1,3-butadiene.

For cases of partial lifetime exposure where time-to-tumor or time-to-tumor death is known, Crump and Howe (1983a) have developed the multistage model to include a time-dependent dose pattern. The form of this model is one which is linear in dose and in which time has a power and form determined by both the number of assumed stages and the stage affected by the carcinogen. A best fit is determined by the method of maximum likelihood in the ADOLL183 computer program (Crump and Howe, 1983b). Application of this program to the NTP data was unsuccessful because of lack of convergence.

4.4.1.2. Selection of Data--For some chemicals, several studies in different animal species, strains, and sexes, each run at several doses and different routes of exposure, are available. A choice must be made as to which of the data sets from several studies to use in the model. It may also be appropriate to correct for metabolism differences between species and for absorption factors via different routes of administration. The procedures used in evaluating these data are consistent with the approach of making a maximum-likely risk estimate. They are listed below:

1. The tumor incidence data are separated according to organ sites or tumor types. The set of data (i.e., dose and tumor incidence) used in the

model is the set in which the incidence is statistically significantly higher than for the control for at least one test dose level, or in which the tumor incidence rate shows a statistically significant trend with respect to dose level, or in which a specific tumor appears unusually early for that site. The data set that gives the highest estimate of the lifetime carcinogenic risk, q_1^*, is selected in most cases. However, efforts are made to exclude data sets that produce spuriously high risk estimates because of a small number of animals. That is, if two sets of data show a similar dose-response relationship, and one has a very small sample size, the set of data having the larger sample size is selected for calculating the carcinogenic potency.

2. If there are two or more data sets of comparable size that are identical with respect to species, strain, sex, and tumor sites, the geometric mean of q_1^*, estimated from each of these data sets, is used for risk assessment. If, as is the case with the 1,3-butadiene NTP (1984) study, males and females of the species show a basically similar response, the usual procedure would be to use the geometric mean of their individual q_1^*'s for the incremental 95% upper-limit unit risk.

3. If two or more significant tumor sites are observed in the same study, and if the data are available, the number of animals with at least one of the specific tumor sites under consideration is used as incidence data in the model.

4.4.1.3. Calculation of Human Equivalent Dosages from Animal Data--Following the suggestion of Mantel and Schneiderman (1975), it is assumed that mg/surface area/day is an equivalent dose between species. Since, to a close approximation, surface area is proportional to the two-thirds power of weight, as would be the case for a perfect sphere, the exposure in mg/day per two-thirds power of the weight is also considered to be equivalent exposure. In an animal experiment, this equivalent dose is computed in the following manner:

Let

L_e = duration of experiment

l_e = duration of exposure

m = average dose per day in mg during administration of the agent (i.e., during l_e), and

W = average weight of the experimental animal

The lifetime exposure is then

$$d = \frac{l_e \times m}{L_e \times W^{2/3}}$$

1,3-Butadiene is slightly soluble in water and can be considered a partially soluble vapor. The dose in m = mg/day of partially soluble vapors is proportional to the O_2 consumption, which in turn is proportional to $W^{2/3}$ and is also proportional to the solubility of the gas in body fluids, which can be expressed as an absorption coefficient, r, for the gas. Therefore, expressing the O_2 consumption as $O_2 = k\ W^{2/3}$, where k is a constant independent of species and V = mg/m^3 of the agent in air, it follows that:

$$m = k\ W^{2/3} \times v \times r$$

or

$$d = \frac{m}{W^{2/3}} = kvr$$

In the absence of experimental information or a sound theoretical argument to the contrary, the absorption fraction, r, is assumed to be the same for all

species. Therefore, for these substances (e.g., 1,3-butadiene) a certain concentration in ppm or $\mu g/m^3$ in experimental animals is assumed equivalent to the same concentration in humans. This is supported by the observation that the minimum alveolar concentration necessary to produce a given "stage" of anesthesia is similar in man and animals (Dripps et al., 1977). When the animals are exposed via the oral route and human exposure is via inhalation or vice versa, the assumption is made, unless there is pharmacokinetic evidence to the contrary, that absorption is equal by either exposure route.

4.4.1.4. Calculation of the Unit Risk from Animal Studies--The risk associated with d $mg/kg^{2/3}/day$ is obtained from GLOBAL83 and, for most cases of interest to risk assessment, can be adequately approximated by $P(d) = 1 - \exp(-q^*d)$. An incremental "unit risk" in units X is simply the risk corresponding to an exposure of X = 1. To estimate this value, the number of $mg/kg^{2/3}/day$ corresponding to one unit of X is determined and substituted into the above relationship. Thus, for example, if X is in units of ppm or $\mu g/m^3$ in the air, then for 1,3-butadiene, d = 1, when ppm or $\mu g/m^3$ is the unit used to compute parameters in animal experiments.

If exposures are given in terms of ppm in air, then the conversion factor to mg/m^3 is

$$1 \text{ ppm} = 1.2 \times \frac{\text{molecular weight (gas)}}{\text{molecular weight (air)}} \text{ mg/m}^3$$

4.4.1.4.1. Adjustments for less than lifetime duration of experiment--When analyzing quantal data, if the duration of experiment L_e is less than the natural lifespan of the test animal L, the slope q^*_1, or more generally the exponent g(d), is increased by multiplying by a factor $(L/L_e)^3$. We assume that

if the average dose d had been continued, the age-specific rate of cancer would have continued to increase as a constant function of the background rate. The age-specific rates for humans increase at least by the second power of the age and often by a considerably higher power, as demonstrated by Doll (1971). Thus, it is expected that the cumulative tumor rate would increase by at least the third power of age. Using this fact, it is assumed that the slope q_1^*, or more generally the exponent g(d), would also increase by at least the third power of age. As a result, if the slope q_1^* [or g(d)] is calculated at age L_e, we expect that if the experiment had been continued for the full lifespan, L, at the given average exposure, the slope q_1^* [or g(d)] would have been increased by at least $(L/L_e)^3$.

For time-to-tumor data, this adjustment is also conceptually consistent with the proportional hazard model proposed by Cox (1972) and the time-to-tumor model considered by Crump (1979), where the probabiity of cancer by age t and at dose d is given by

$$P(d,t) = 1 - \exp[-f(t) \times g(d)].$$

It is also consistent with the partial lifetime exposure extension of the multistage model developed by Crump and Howe (1983a), which as discussed above is linear in dose, but has a power function of time.

4.4.1.5. Interpretation of Quantitative Estimates--For several reasons, the unit risk estimate based on animal bioassays is only an approximate indication of the absolute risk in populations exposed to known carcinogen concentrations. First, there are important species differences in uptake, metabolism, and organ distribution of carcinogens, as well as species differences in target site susceptibility, immunological responses, hormone function, dietary factors, and

disease. Second, the concept of equivalent doses for humans compared to animals on a mg/surface area basis is virtually without experimental verification regarding carcinogenic response. Finally, human populations are variable with respect to genetic constitution and diet, living environment, activity patterns, and other cultural factors.

The unit risk estimate can give a rough indication of the relative potency of a given agent as compared with other carcinogens. The comparative potency of different agents is more reliable when the comparison is based on studies in the same test species, strain, and sex, and by the same route of exposure, preferably inhalation.

The quantitative aspect of carcinogen risk assessment is included here because it may be of use in the regulatory decision-making process, e.g., setting regulatory priorities, evaluating the adequacy of technology-based controls, etc. However, it should be recognized that the estimation of cancer risks to humans at low levels of exposure is uncertain. Because of the limited data available from animal bioassays, especially at the high dose levels required for testing, almost nothing is known about the true shape of the dose-response curve at low environmental levels. At best, the linear extrapolation model used here provides a rough but plausible estimate of the upper limit of risk; i.e., it is not likely that the true risk would be much more than the estimated risk, but it could be considerably lower. The risk estimates presented in subsequent sections should not be regarded as accurate representations of the true cancer risk even when the exposures are accurately defined. The estimates presented may, however, be factored into regulatory decisions to the extent that the concept of upper risk limits is found to be useful.

4.4.1.6. Alternative Models--The methods used by the CAG for quantitative extrapolation from animal to man are generally conservative, i.e., tending toward

high estimates of risk. The most important part of the methodology contributing to this conservatism is the CAG's use of the linearized multistage non-threshold extrapolation model. There are a variety of other extrapolation models that could be used, most of which would give lower risk estimates. Among these alternative models, two which are currently popular and which often tend to give different low-dose extrapolations than the multistage model are the log-probit and Weibull models. These models have not been used in the following analysis of the mouse data because their fits to the 1,3-butadiene data base were considered poorer than that of the mulcistage model. As discussed below, all models are of limited value for predicting low-dose risks for 1,3-butadiene because mouse responses were greater than 60% at the lowest dose tested, and rat responses were far less sensitive than those of the mouse.

4.4.2. Calculation of Quantitative Estimates

Human studies have provided inadequate evidence for the carcinogenicity of 1,3-butadiene. Furthermore, concurrent exposure to several other possible carcinogens also limits the use of epidemiologic studies as primary sources for calculating quantitative risk estimates. For animal-to-human extrapolation, there are two suitable animal bioassays, both showing significant carcinogenic response. The first, a rat inhalation study, showed statistically significant increases in several tumor sites in both males and females (Hazleton Laboratories, Ltd., 1981a). The second study was the NTP (1984) mouse inhalation study, which showed high statistically significant increases ($p < 0.01$) both in hemangiosarcomas of the heart and malignant lymphomas and in both males and females at 625 ppm and 1,250 ppm. Both of these tumor types are life-threatening and appeared quite early in the study. As discussed at length in the qualitative section and shown in Table 8, several other tumor sites were also significantly increased in the study, which was stopped at 60-61 weeks due to

high mortality from tumors in the treated groups.

The mice were used for risk estimation, since they were far more sensitive than the rats. Incremental 95% upper-limit unit risk estimates were calculated from both the male and female mouse data. For the male mice, the numbers of animals either with tumors at significantly increased sites, or with tumors considered unusual for 60 weeks (preputial gland squamous cell carcinomas and Zymbal gland carcinomas (see Table 10) were 2/50, 43/50, and 40/50 for the control, 625-ppm, and 1,250-ppm groups, respectively. For the females, the numbers of animals with significantly increased tumors or brain gliomas were 4/50, 31/49, and 45/49. These results are presented in Table 11. Also presented in Table 11 are the maximum likelihood estimates (MLE) and the 95% upper-limit unit risk estimates (q_1^*) based on these data. The initial upper-limit estimates based on the 60-week (male) and 61-week (female) studies are then adjusted to project for natural lifetime risk (see section 4.4.1.4.1.). The final estimates are $q_1^* = 7.1 \times 10^{-2}$ $(ppm)^{-1}$ for the males and $q_1^* = 5.9 \times 10^{-2}$ $(ppm)^{-1}$ for the females. Since the data sets are so comparable, the geometric mean, $q_1^* = 6.5 \times 10^{-2}$ $(ppm)^{-1}$, was chosen as the final 95% upper-limit unit risk estimate.

This estimate can also be presented in terms of $\mu g/m^3$. The conversion factor is

$$1 \text{ ppb} = 1.2 \times \frac{\text{M.W. 1,3-butadiene}}{\text{M.W. air}} = 1.2 \times \frac{54.1}{28.8} \mu g/m^3$$

or $$1 \text{ ppb} = 2.25 \mu g/m^3$$

or $$1 \text{ ppm} = 2.25 \times 10^3 \mu g/m^3$$

TABLE 11. NUMBERS OF MICE WITH AT LEAST ONE OF THE STATISTICALLY SIGNIFICANT INCREASED TUMORS, OR TUMORS CONSIDERED UNUSUAL AT TIME OF TERMINAL SACRIFICE. ALSO, MLE AND 95%-UPPER-LIMIT INCREMENTAL UNIT RISK ESTIMATES[a]

Nominal exposure (ppm)	Equivalent continuous exposure[b] (ppm)	No. males with tumors/ no. examined[c]	No. females with tumors/ no. examined[c]
0	0	2/50 (4%)	4/50 (8%)
625	111.6	43/50 (86%)	31/49 (63%)
1,250	223.2	40/50 (80%)	45/49 (92%)

[a]See Tables 8 and 10 for tumor sites.
[b]Continuous equivalent dose = animal exposure x 6/24 x 5/7.
[c]Examined for either hemangiosarcomas or lymphomas.

	Males	Females
Initial maximum likelihood estimates	$q_1 = 8.1 \times 10^{-3}$ (ppm)$^{-1}$	$q_1 = 1.0 \times 10^{-2}$ (ppm)$^{-1}$
Initial estimates of 95% upper limit	$q_1^* = 1.36 \times 10^{-2}$ (ppm)$^{-1}$	$q_1^* = 1.18 \times 10^{-2}$ (ppm)$^{-1}$
Adjustment factor for early sacrifice	$(\frac{104}{60})^3 = 5.21$	$(\frac{104}{61})^3 = 4.96$
Final estimate of 95% upper limit	7.1×10^{-2} (ppm)$^{-1}$	5.9×10^{-2} (ppm)$^{-1}$
Geometric mean of 95% upper limit	$q_1^* = 6.5 \times 10^{-2}$ (ppm)$^{-1}$	

then $q_1^* = 6.5 \times 10^{-2}\ (\text{ppm})^{-1} \times \frac{1}{2.25 \times 10^3\ \mu g/m^3} = 2.9 \times 10^{-5}\ (\mu g/m^3)^{-1}$

4.4.3. Comparison of Human and Animal Inhalation Studies

The purpose of this section is to evaluate whether or not the animal-to-man extrapolated estimate of 1,3-butadiene-caused cancer is reasonably borne out by human data. The section considers the limited data base and determines to what extent extrapolation from the positive animal data might overestimate the human response.

While mouse exposures of 625 ppm and 1,250 ppm of 1,3-butadiene (6 hours/day, 5 days/week for 60-61 weeks) caused a broad spectrum of cancers, human response associated with the SBR process was not consistent across studies. Various cohorts displayed excess mortality from cancers of the stomach or intestine, prostate, and/or respiratory system. The most consistent excesses (and, therefore, the focus of this section) appear to be restricted to cancers of the lymphatic and hematopoietic systems, cancers which include leukemias, Hodgkin's disease, and lymphosarcomas.

It must be emphasized that exposure to 1,3-butadiene alone cannot be isolated from exposure to several other potential carcinogens. Especially associated with the SBR process is concurrent exposure to styrene, a compound for which there is limited evidence of carcinogenicity in animals and inadequate evidence in humans (IARC, 1982). The small amount of human evidence associated with styrene exposure and cancer suggests an association with leukemia and, possibly, lymphomas. Styrene, like 1,3-butadiene, metabolizes to an epoxide; both epoxides are the suspected carcinogens. (Ethylene oxide, also an epoxide, is also associated with leukemias). In addition to styrene, the SBR process

involves numerous other exposures concurrent with 1,3-butadiene. These concurrent exposures will not be dealt with in the following analysis, because if the animal risk extrapolation based on 1,3-butadiene alone overestimates the human risk, then the animal risk extrapolation will most likely be too high.

Probably the strongest evidence for human cancer associated with the SBR process is that of Meinhardt et al. (1982), in which workers exposed to the high-temperature batch polymerization process from 1943 through 1945 showed a marginally significant increase in cancers of the lymphatic and hematopoietic tissues, with an SMR of 212 from 9 deaths out of 600 study members. For workers first exposed after the process was changed to continuous feed in 1946, with correspondingly less exposure, no deaths from lymphopoietic system cancers occurred among more than 1,000 study members. Unfortunately, no exposure estimates are available for the pre-1946 cohort. For the cohort exposed after 1946, only 1,3-butadiene measurements taken after 1975 are available. They show an 8-hour time-weighted average mean concentration of 1.24 ppm butadiene (± 1.20 standard deviation [SD]), 0.10 ppm benzene (± 0.035 SD), and 0.94 ppm styrene (± 1.23 SD). (Benzene is not used in SBR manufacturing, but may be present as an impurity of styrene or toluene.) The Meinhardt et al. (1982) study also contained an analysis from a second plant whose workers were first exposed in 1950. Based on a cohort of 1,094, the SMR for cancers of the lymphatic and hematopoietic tissues was 78, slightly higher than the overall SMR of 66, the latter being significantly ($p < 0.05$) less than that of the comparable general population. Meinhardt et al. reported average 1,3-butadiene exposure levels in 1977 of 13.5 ppm.

The next strongest evidence for cancer associated with the SBR process is based on the case-control study of McMichael et al. (1976). These authors estimated an age-standardized risk ratio of 6.2 for lymphatic and hematopoietic

cancers among workers with at least 5 years of exposure in the synthetic plant, relative to all other workers as controls. (This ratio decreased to 2.4 when a matched control analysis was used.) The synthetic plant is where the SBR process is located. McMichael et al. also found a dose-related risk ratio in the synthetic plant by number of years worked there.

Estimates of exposures in the McMichael et al. study are based upon a later paper. Checkoway and Williams (1982) measured 1,3-butadiene, styrene, benzene, and toluene levels at the same synthetic plant in which McMichael et al. (1976) found that "leukemia and lymphoma (cases) among hourly paid rubber workers from one company were 6 times more likely than controls to have worked at jobs in the SBR plant." Exposure levels of 1,3-butadiene typically averaged below 1 ppm, but exposure levels in the tank farm area averaged 20 ppm.

The most extensive investigation specifically designed to study the health effects of the SBR process shows very little association of 1,3-butadiene with lymphatic and hematopoietic tissue cancer (ICD 200-207). The Matanoski et al. study of one Canadian and seven U.S. synthetic rubber plants showed, possibly, a trend with more exposure as defined by production, maintenance, utilities, or other jobs, but none of the SMRs (Table 12) are statistically significant. Only Hodgkin's disease (ICD 201), shows a consistently high SMR in all three cohorts, but the numbers of cases were small. No exposure estimates were presented in the Matanoski et al. report, but the plants studied were of the same type as those studied by Meinhardt et al. Some workers in seven of the eight plants might have started as early as 1943, and Matanoski states (personal communication) that the open batch process in several of these plants was continued into the early 1970s. Based on these observations, the estimates of 20 ppm for production workers, 10 ppm for maintenance workers, and 5 ppm for utility workers have been used for calculation purposes.

TABLE 12. SUMMARY OF CANCER OF LYMPHATIC AND HEMATOPOIETIC TISSUES ASSOCIATED WITH THE STYRENE-BUTADIENE SYNTHETIC RUBBER PROCESS. CONFIDENCE LIMITS ON ACTUAL SMRs PREDICTED EXCESS DEATHS BASED ON INITIAL MLE INCREMENTAL UNIT RISKS OF THE MOUSE DATA

Study	Sample size	Cancer type	Observed	Expected	SMR	95% Confidence intervals	Excess deaths from exposure predicted from mouse data (observed-expected)[a]	Power to detect predicted deaths (α=. 0.05)[b]	Comments
Meinhardt et al. (1982)									
Plant A 1943-1945	600	Lymphatic and hematopoietic tissues ICD (200-205)	9	4.25	2.12	0.96-4.02	1.7 (4.75)*[c]	12%	Estimates from 1943-1945: 20 ppm from 1946-1952: 10 ppm
Plant A 1946-1976	1,062	Same as above	0	1.54	0	0-2.34	0.2 (-1.54)	3%	Average exposure = 1.24
Plant B 1950-1976	1,094	Same as above	2	2.55	0.78	0.09-2.83	2.3 (-0.55)	23%	Average exposure = 13.5
Matanoski et al. (1982) (by job last held)									
Production	3,269	All lympho-poietic ICD (200-207)	11	10.6	1.04	0.52-1.86	18.0 (0.4)**	99%	Same types of plants as those studied by Meinhardt et al. Assume: 20 ppm (estimate)
Maintenance	3,683	Same as above	13	16.2	0.80	0.47-1.37	9.3 (-3.2)**	53%	10 ppm (estimate)
Utilities	550	Same as above	4	6.5	0.62	0.17-1.58	0.5 (-2.5)	4%	5 ppm (estimate)
McMichael et al. (1976)		All lym-phatic and hematopoietic (200-209)	--	--	6.2 (risk ratio in synthetic plants 2.4 in matched controls	No further estimates possible	--	--	Increases associated with compounding, mixing, cement mixing, inspection-finishing-repair, synthetic plant. Average exposure < 1 ppm except for tank farm area (20 ppm)

[a]Test for observed cancers not significantly different from predicted (Poisson test or normal approximation to the Poisson).
[b]$\alpha = 0.05$, power determined by formula $Z_{1-\beta} = Z_{\alpha} - 2 (SMR^{0.5} - 1)E^{0.5}$ (Beaumont and Breslow, 1981).
[c]More deaths predicted than observed.
*$p < 0.05$.
**$p < 0.01$.

Is the unit risk estimate based on the mouse tumor data a reasonable extrapolation? To answer this question we must be able to estimate the predicted effect based on actual (or estimated) exposure. (We must also assume the effect on these cancers from other exposures to be nil.) For illustration, we choose the Meinhardt et al. (1982) study plant B, with estimated exposure of 13.5 ppm. Although this exposure was measured in 1977, we will consider it to be representative of exposures from 1950 through 1976. We must also know that the 1,094 study members converted to 19,742 person-years at risk for an average of 18 years per person. Since average employment or exposure is given as 10.78 years, we can estimate the expected contribution as follows:

1. The continuous lifetime equivalent exposure based on 10 working years out of about 50 possible remaining years is:

$$13.5 \text{ ppm} \times \frac{10.78}{50} \text{ years} \times \frac{240}{365} \text{ day} \times \frac{8}{24} \text{ hours} = 0.64 \text{ ppm}$$

2. The inital best estimate (MLE) of risk based on the mouse data is $q_1 = 8.1 \times 10^{-3}$ $(\text{ppm})^{-1}$ for the males, $q_1 = 1.0 \times 10^{-2}$ $(\text{ppm})^{-1}$ for the females, and a geometric mean of $q_1 = 9.0 \times 10^{-3}$ $(\text{ppm})^{-1}$, based on human equivalent continuous exposure. This geometric mean MLE incremental risk estimate will be used to predict human excess deaths for the present purpose of deciding whether the number of deaths among industrial workers is consistent with the expected deaths derived using the animal extrapolation procedure. The initial estimate (Table 11) is used since it projects the limited animal observation period (60-61 weeks out of a 2-year lifetime) to the the limited human observation period (average of up to 29 years out of 50 years remaining lifetime).

3. Based on the unit risk factor $q_1 = 9.0 \times 10^{-3}$ (ppm)$^{-1}$, each of the 1,094 workers would be expected to have an additional lifetime risk of

$$R = 9.0 \times 10^{-3} \text{ (ppm)}^{-1} \times 0.64 = 5.8 \times 10^{-3}$$

4. Based on 1,094 workers at risk for 18 of their 50 remaining years, this converts to the following expected excess number of cancers:

$$5.8 \times 10^{-3} \times 1{,}094 \times \frac{18}{50} = 2.3$$

5. In addition to the 2.55 cancer deaths expected based on no exposure (Table 12), we could expect, with the exposure, to observe 4.8 deaths from cancers of the lymphatic and hematopoietic tissues. The probability of observing two or fewer deaths (Table 12) with 4.8 expected is

$$P \text{ (deaths } \leq 2 | \lambda = 4.8) = \sum_{x=0}^{2} \frac{e^{-\lambda} \lambda^{x}}{x!} = 0.14$$

The statistical power to detect a predicted SMR of (4.8/2.55) or 1.9 is given by Beaumont and Breslow (1981) as $Z_{1-\beta} = Z_{\alpha} - 2 (SMR^{0.5} - 1)E^{0.5}$. For plant B this is

$$Z_{1-\beta} = 1.96 - 2 (1.9^{0.5} - 1) (2.55)^{0.5} = 0.75$$

which corresponds to a power of 0.23, or 23% at $\alpha = 0.05$.

Results based on similar calculations are presented in Table 12 for the other two Meinhardt cohorts and for three Matanoski cohorts. They show inconsistent results. For the 1943-1945 plant A Meinhardt cohort, the deaths preicted from animal extrapolation actually underpredict the observed human response ($p < 0.5$). For the other two Meinhardt cohorts and the Matanoski utilities cohort, the predicted and observed results are not significantly different, although the power to detect the predicted difference in these three cases is low--23% or less. For the two larger Matanoski cohorts, the extrapolated deaths do significantly ($p < 0.01$ in both cases) overpredict response. Furthermore, the power to detect the predicted response is 99% in the maintenance cohort.

The interpretation of these results, if we dismiss momentarily the large uncertainties in the exposure estimates, is that no predicted results will satisfy the observed results in all six cohorts. Were we to lower the risk estimates to try to better accommodate the Matanoski maintenance and production cohorts, we would further underestimate the observed results for the Meinhardt and early plant A cohort. Based on the information we have, no single extrapolated value can predict the human response. It seems probable that the potency value we have extrapolated will overpredict human response by a factor of about 3. Considering the uncertainties in the human exposure data, however, the animal extrapolation is the best that can be achieved at present.

Finally, the same analysis as computed for lymphatic and hematopoietic cancers in Table 12, can be done for all cancers on the theory that 1,3-butadiene might be a broad-spectrum carcinogen in humans as it is in mice. This analysis is presented in Table 13. Since we have used the same extrapolation from the mouse data, the same number of excess deaths as predicted in Table 12 will result, but these excess deaths are spread out over all cancers. It should

TABLE 13. SUMMARY OF ALL CANCERS (ICD 140-205) ASSOCIATED WITH THE STYRENE-BUTADIENE SYNTHETIC RUBBER PROCESS. CONFIDENCE LIMITS ON ACTUAL SMRs PREDICTED EXCESS DEATHS BASED ON INITIAL MLE INCREMENTAL UNIT RISKS OF THE MOUSE DATA

Study	Sample size	All cancers (ICD 140-205) Observed	Expected	SMR	95% confidence intervals	Excess deaths from exposure predicted from mouse data (observed-expected)[a]	Power to detect predicted deaths (α= 0.05)[b]	Comments
Meinhardt et al. (1982)								
Plant A 1943-1945	600	39	45.14	0.86	0.63-1.18	1.7 (-6.14)	5%	Estimates from 1943-1945: 20 ppm from 1946-1952: 10 ppm
Plant A 1946-1976	1,062	10	12.19	0.82	0.45-1.51	0.2 (-2.19)	3%	Average exposure = 1.24
Plant B 1950-1976	1,094	11	20.78	0.58	30-0.95*	2.3 (-9.78)**	7%	Average exposure = 13.5
Matanoski et al. (1982) (by job last held)								Same types of plants as those studied by Meinhardt et al. Assume: 20 ppm (estimate)
Production	3,269	94	105.6	0.89	0.73-1.09	18.0 (-9.6)**	39%	
Maintenance	3,683	168	176.8	0.95	0.82-1.11	9.3 (-8.8)	10%	10 ppm (estimate)
Utilities	550	25	26.3	0.95	0.58-2.07	0.5 (-1.3)	3%	5 ppm (estimate)

[a]Test for observed cancers not significantly different from predicted (Poisson test or normal approximation to the Poisson).
[b]$\alpha = 0.05$, power determined by formula $Z_{1-\beta} = Z_{\alpha} - 2 (SMR^{0.5} - 1)E^{0.5}$ (Beaumont and Breslow, 1981).
[c]More deaths predicted than observed.
*$p < 0.05$.
**$p < 0.01$.

be noted that only one of the SMRs is statistically significant and that all, in fact, are less than one. Based on the predicted excess deaths extrapolated from animal data and estimated exposures, two of the cohorts experienced significantly fewer deaths than predicted. For one of these cohorts, the Meinhardt plant B, the deficit in observed versus expected deaths was significant even if there were no predicted deaths. For the other, the Matanoski production workers, a reduction of predicted deaths from 18 to 6 would eliminate statistical significance at the $p = 0.05$ level (one-sided). This corresponds to a reduction of the extrapolated unit risk estimate by a factor of 3. This is the only cohort with a power greater than 10%--it has a power of 39%--of detecting the predicted results.

Comparing Tables 12 and 13, we see fairly similar results: weak, if any, evidence of a human carcinogenic risk from 1,3-butadiene, but also no strong evidence that the unit risk extrapolation from animal to human results is unreasonable, or that it seriously overpredicts a potential risk.

4.4.4. Relative Potency

One of the uses of quantitative estimation is to compare the relative potencies of different carcinogens. To estimate relative potency, the unit risk slope factor is multiplied by the molecular weight, and the resulting number is expressed in terms of $(mmol/kg/day)^{-1}$. This is called the relative potency index.

Figure 2 is a histogram representing the frequency distribution of potency indices of 54 suspect carcinogens evaluated by the CAG. The actual data summarized by the histogram are presented in Table 14. Where positive human data are available for a compound, they have been used to calculate the index. Where no human data are available, animal oral studies and animal inhalation studies have been used, in that order. In the present case, only the animal inhalation studies

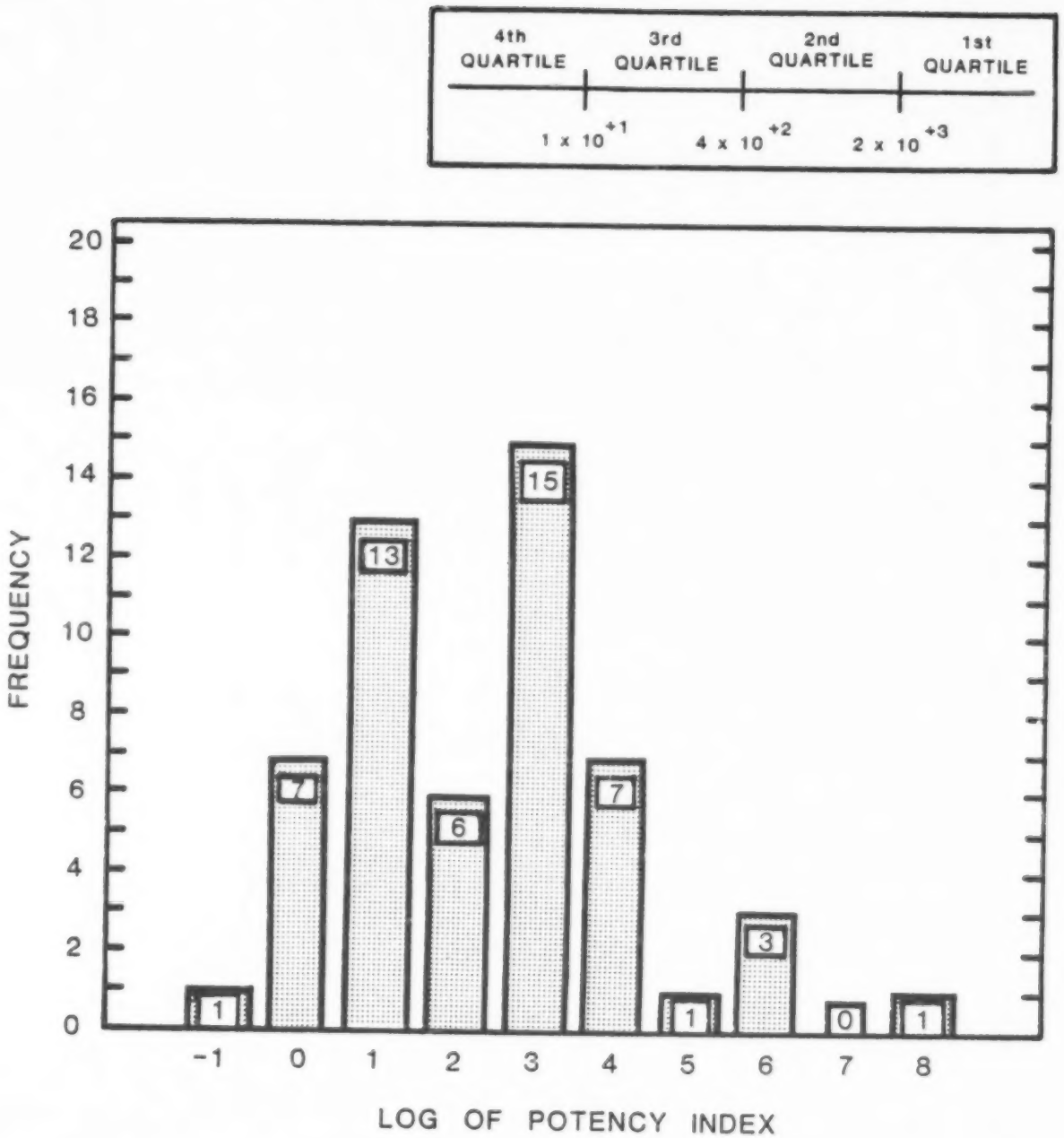

Figure 2. Histogram representing the frequency distribution of the potency indices of 54 suspect carcinogens evaluated by the Carcinogen Assessment Group.

TABLE 14. RELATIVE CARCINOGENIC POTENCIES AMONG 54 CHEMICALS EVALUATED BY THE CARCINOGEN ASSESSMENT GROUP AS SUSPECT HUMAN CARCINOGENS

Compounds	CAS Number	Level of evidence[a]		Grouping based on IARC criteria	Slope (mg/kg/day)-1	Molecular weight	Potency index	Order of magnitude (log_{10} index)
		Humans	Animals					
Acrylonitrile	107-13-1	L	S	2A	0.24(W)	53.1	$1x10^{+1}$	+1
Aflatoxin B_1	1162-65-8	L	S	2A	2900	312.3	$9x10^{+5}$	+6
Aldrin	309-00-2	I	L	2B	11.4	369.4	$4x10^{+3}$	+4
Allyl chloride	107-05-1				$1.19x10^{-2}$	76.5	$9x10^{-1}$	0
Arsenic	7440-38-2	S	I	1	15(H)	149.8	$2x10^{+3}$	+3
B[a]P	50-32-8	I	S	2B	11.5	252.3	$3x10^{+3}$	+3
Benzene	71-43-2	S	S	1	$2.9x10^{-2}$(W)	78	$2x10^{0}$	0
Benzidene	92-87-5	S	S	1	234(W)	184.2	$4x10^{+4}$	+5
Beryllium	7440-41-7	L	S	2A	2.6	9	$2x10^{+1}$	+1
1,3-Butadiene	106-99-0	I	S	2B	$1.0x10^{-1}$(I)	54.1	$5x10^{0}$	+1
Cadmium	7440-43-9	L	S	2A	7.8(W)	112.4	$9x10^{+2}$	+3
Carbon tetrachloride	56-23-5	I	S	2B	$1.30x10^{-1}$	153.8	$2x10^{+1}$	+1
Chlordane	57-74-9	I	L	3	1.61	409.8	$7x10^{+2}$	+3

[a]S = Sufficient evidence; L = Limited evidence; I = Inadequate evidence.

(continued on the following page)

TABLE 14. (continued)

Compounds	CAS Number	Level of evidence[a] Humans	Animals	Grouping based on IARC criteria	Slope (mg/kg/day)-1	Molecular weight	Potency index	Order of magnitude (log_{10} index)
Chlorinated ethanes								
1,2-dichloroethane	107-06-2	I	S	2B	6.9x10-2	98.9	7x100	+1
hexachloroethane	67-72-1	I	L	3	1.42x10-2	236.7	3x100	0
1,1,2,2-tetrachloroethane	79-34-5	I	L	3	0.20	167.9	3x10+1	+1
1,1,2-trichloroethane	79-00-5	I	L	3	5.73x10-2	133.4	8x100	+1
Chloroform	67-66-3	I	S	2B	7x10-2	119.4	8x100	+1
Chromium	7440-47-3	S	S	1	41(W)	100	4x10+3	+4
DDT	50-29-3	I	S	2B	0.34	354.5	1x10+2	+2
Dichlorobenzidine	91-94-1	I	S	2B	1.69	253.1	4x10+2	+3
1,1-Dichloroethylene (Vinylidene chloride)	75-35-4	I	L	3	1.47x10-1(I)	97	1x10+1	+1
Dichloromethane (Methylene chloride)	75-09-2	I	L	3	6.3x10-4(I)	84.9	5x10-2	-1
Dieldrin	60-57-1	I	S	2B	30.4	380.9	1x10+4	+4
2,4-Dinitrotoluene	121-14-2	I	S	2B	0.31	182	6x10+1	+2
Diphenylhydrazine	122-66-7	I	S	2B	0.77	180	1x10+2	+2
Epichlorohydrin	106-89-8	I	S	2B	9.9x10-3	92.5	9x10-1	0
Bis(2-chloroethyl)ether	111-44-4	I	S	2B	1.14	143	2x10+2	+2

[a]S = Sufficient evidence; L = Limited evidence; I = Inadequate evidence.

(continued on the following page)

TABLE 14. (continued)

Compounds	CAS Number	Level of evidence[a] Humans	Level of evidence[a] Animals	Grouping based on IARC criteria	Slope (mg/kg/day)-1	Molecular weight	Potency index	Order of magnitude (log_{10} index)
Bis(chloromethyl)ether	542-88-1	S	S	1	9300(I)	115	$1x10^{+6}$	+6
Ethylene dibromide (EDB)	106-93-4	I	S	2B	41	187.9	$8x10^{+3}$	+4
Ethylene oxide	75-21-8	L	S	2A	$3.5x10^{-1}$(I)	44.1	$2x10^{+1}$	+1
Heptachlor	76-44-8	I	S	2B	3.37	373.3	$1x10^{+3}$	+3
Hexachlorobenzene	118-74-1	I	S	2B	1.67	284.4	$5x10^{+2}$	+3
Hexachlorobutadiene	87-68-3	I	L	3	$7.75x10^{-2}$	261	$2x10^{+1}$	+1
Hexachlorocyclohexane technical grade					4.75	290.9	$1x10^{+3}$	+3
alpha isomer	319-84-6	I	S	2B	11.12	290.9	$3x10^{+3}$	+3
beta isomer	319-85-7	I	L	3	1.84	290.9	$5x10^{+2}$	+3
gamma isomer	58-89-9	I	L	2B	1.33	290.9	$4x10^{+2}$	+3
Hexachlorodibenzodioxin	34465-46-8	I	S	2B	$6.2x10^{+3}$	391	$2x10^{+6}$	+6
Nickel	7440-02-0	L	S	2A	1.15(W)	58.7	$7x10^{+1}$	+2
Nitrosamines								
Dimethylnitrosamine	62-75-9	I	S	2B	25.9(not by q_1^*)	74.1	$2x10^{+3}$	+3
Diethylnitrosamine	55-18-5	I	S	2B	43.5(not by q_1^*)	102.1	$4x10^{+3}$	+4
Dibutylnitrosamine	924-16-3	I	S	2B	5.43	158.2	$9x10^{+2}$	+3

[a]S = Sufficient evidence; L = Limited evidence; I = Inadequate evidence.

(continued on the following page)

TABLE 14. (continued)

Compounds	CAS Number	Level of evidence[a] Humans	Animals	Grouping based on IARC criteria	Slope (mg/kg/day)-1	Molecular weight	Potency index	Order of magnitude (log_{10} index)
N-nitrosopyrrolidine	930-55-2	I	S	2B	2.13	100.2	$2x10^{+2}$	+2
N-nitroso-N-ethylurea	759-73-9	I	S	2B	32.9	117.1	$4x10^{+3}$	+4
N-nitroso-N-methylurea	684-93-5	I	S	2B	302.6	103.1	$3x10^{+4}$	+4
N-nitroso-diphenylamine	86-30-6	I	S	2B	$4.92x10^{-3}$	198	$1x10^{0}$	0
PCBs	1336-36-3	I	S	2B	4.34	324	$1x10^{+3}$	+3
Phenols								
2,4,6-Trichlorophenol	88-06-2	I	S	2B	$1.99x10^{-2}$	197.4	$4x10^{0}$	+1
Tetrachlorodibenzo-p-dioxin (TCDD)	1746-01-6	I	S	2B	$1.56x10^{+5}$	322	$5x10^{+7}$	+8
Tetrachloroethylene	127-18-4	I	L	3	$6.0x10^{-2}$	165.8	$1x10^{1}$	+1
Toxaphene	8001-35-2	I	S	2B	1.13	414	$5x10^{+2}$	+3
Trichloroethylene	79-01-6	I	L/S	3/2B	$1.2x10^{-2}$	131.4	$2x10^{0}$	0
Vinyl chloride	75-01-4	S	S	1	$1.75x10^{-2}(I)$	62.5	$1x10^{0}$	0

[a]S = Sufficient evidence; L = Limited evidence; I = Inadequate evidence.

Remarks:

1. Animal slopes are 95% upper-limit slopes based on the linearized multistage model. They are calculated based on animal oral studies, except for those indicated by I (animal inhalation), W (human occupational exposure), and H (human drinking water exposure). Human slopes are point estimates based on the linear nonthreshold model.

2. The potency index is a rounded-off slope in (mmol/kg/day)-1 and is calculated by multiplying the slopes in (mg/kg/day)-1 by the molecular weight of the compound.

3. Not all of the carcinogenic potencies presented in this table represent the same degree of certainty. All are subject to change as new evidence becomes available.

provide sufficient evidence of carcinogenicity and have sufficient exposure information.

The potency index for 1,3-butadiene based on the NTP mouse inhalation study (NTP, 1984) is 5.4 $(mmol/kg/day)^{-1}$. This is derived as follows: the upper-limit incremental unit risk estimate from the inhalation study is 2.9×10^{-5} $(\mu g/m^3)^{-1}$. Transforming this to mg/kg/day, the conversion factor is

$$1\ \mu g/m^3 = 1\ \mu g/m^3 \times 20\ m^3/day \times 10^{-3}\ mg/\mu g \times 1/70\ kg = 2.86 \times 10^{-4}\ mg/kg/day$$

Then

$$q_1^* = 2.9 \times 10^{-5}\ (\mu g/m^3)^{-1} \times \frac{1}{2.86} \times 10^{-4}\ mg/kg/day = 1.0 \times 10^{-1}\ (mg/kg/day)^{-1}$$

Multiplying by the molecular weight of 54.1 gives a potency index of 5.4×10^0. Rounding off to the nearest order of magnitude gives a value of 10^1, which is the scale presented on the horizontal axis of Figure 2. The index of 5.4 lies at the top of the fourth quartile of the 54 chemicals that the CAG has evaluated as suspect carcinogens. Thus, in terms of potency alone, 1,3-butadiene would place among the weakest of these carcinogens. However, the fact that 1,3-butadiene causes so many fatal tumors in animals and sharply decreases the latency period increases concern beyond that based simply on relative potency.

4.4.5. Summary of Quantitative Estimation

Based on the linearized multistage model, a 95% upper-limit incremental unit risk was calculated for 1,3-butadiene using the geometric mean of the 95% upper-limit incremental risk estimates from the pooled male and pooled female significant tumor responses of the NTP mouse study. The mean value of $q_1^* = 6.5 \times 10^{-2}\ (ppm)^{-1}$ was then used to predict human responses in several

epidemiologic studies, and the predicted and actual responses were then compared. The comparisons were hampered by a scarcity of information on the epidemiology concerning actual exposures, age distributions, and work histories. In addition, because there was no consistent cancer response across all of the studies, the most predominant response, cancer of the lymphatic and hematopoietic tissues, was chosen as being the target for 1,3-butadiene. Based on the comparisons between the predicted and observed human response, the extrapolated value from the animal data appeared high by a factor of about 3, but in view of the uncertainty and apparent inconsistency of the epidemiologic data, no better estimate can be made at this time.

In addition to a 95% upper-limit incremental unit risk, a measure of carcinogenic potency was determined for 1,3-butadiene. Among the 54 chemicals that the CAG has evaluated as suspected carcinogens, 1,3-butadiene ranks fairly low in potency, placing at the top of the fourth quartile. Based on the wide spectrum of cancers and sharply decreased latency associated with these cancers, however, 1,3-butadiene should evoke much more concern than the potency numbers alone indicate.

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